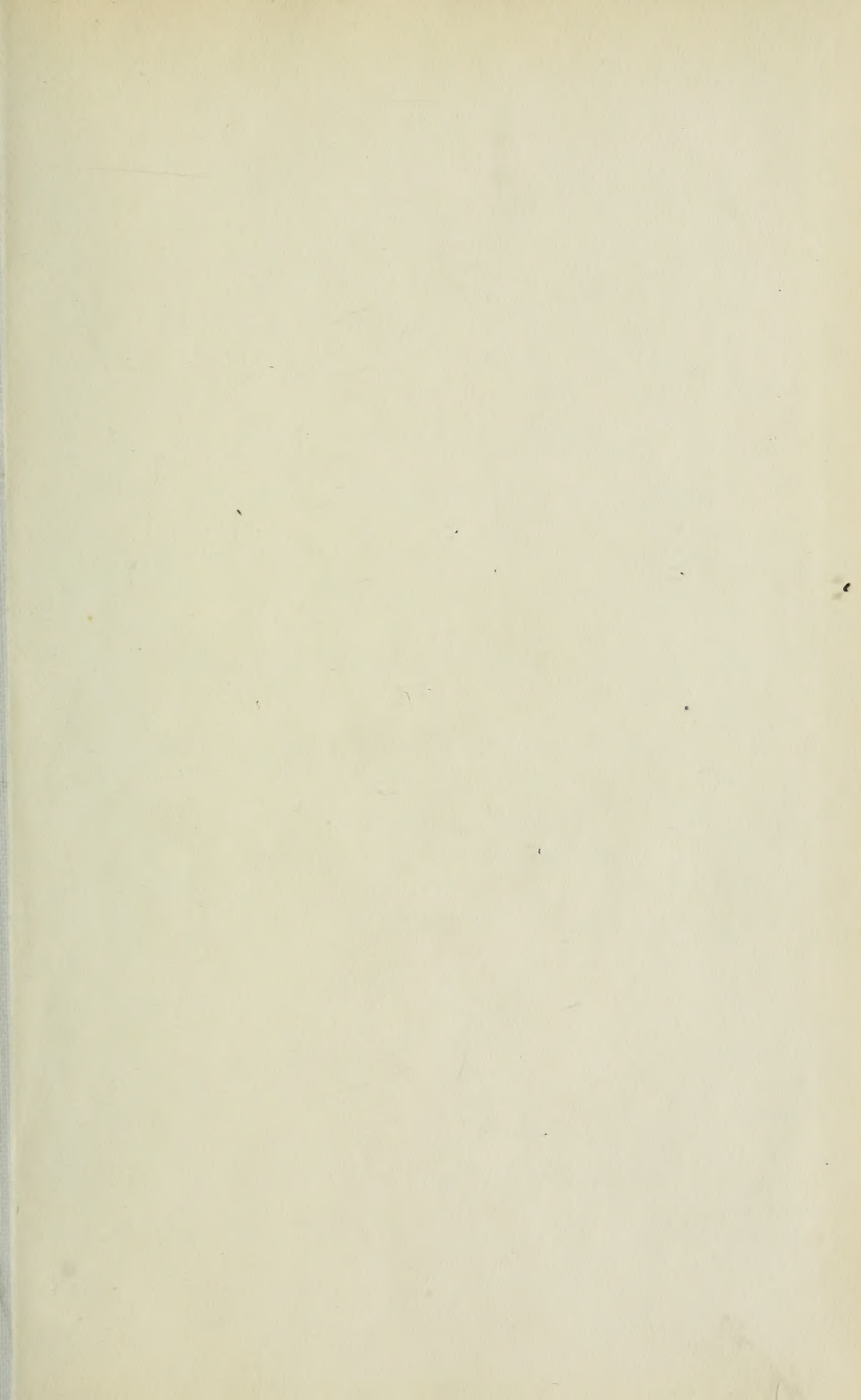


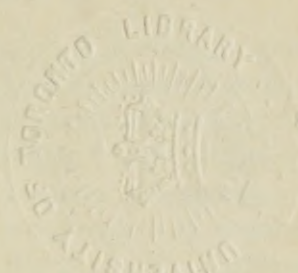
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UNIT COAL AND THE COMPOSITION OF COAL ASH

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I. INTRODUCTION¹

It was recognized at the very outset of these experiments on coal, which were begun in the Laboratory of Industrial Chemistry, University of Illinois, about the year 1897, that much value would attach to any device or method which would make it possible to study the properties, composition, heat values, etc., of the pure coal substance as distinct from the non-coal material with which it is associated. While much data of a general nature accumulated from year to year, having more or less bearing upon this subject, it was not until recent months that a definite study of the problem was undertaken. It is the purpose of this paper to present the results of these investigations upon the properties and more definite determination of actual or unit coal. By unit coal is meant the organic material which is involved in combustion as apart from the mineral constituents which are the extraneous and variable accompaniments of the actual or unit coal.

II. HISTORICAL REVIEW

A number of investigators have worked on various phases of this topic. Lord and Haas, who were no doubt the first in the field, have developed the idea that in any given type of coal, or perhaps, less broadly, in any given deposit of coal, there exists an initial substance, with certain uniformities as to calorific value, which might make it possible to calculate the heat units for any sample whose source as to locality was known.

From numerous analyses of Pennsylvania and Ohio coals, Lord and Haas draw a comparison between the heat values as derived by Du Long's formula, the Mahler calorimeter, and those calculated from unit value which they designate as H , and describe as being the value for the ash, water and sulphur-free substance. They find the sulphur to be a disturbing element and correct for it in a partial manner only. However, they state as their conclusion that "On comparing the results, seam by seam, it would appear

¹Credit is due Mr. W. F. Wheeler for the greater part of the work embodied in this bulletin. Mr. Wheeler died November 18, 1909.

that the actual coal of a given seam, at least over considerable areas, may be regarded as essentially of uniform heating value."¹

The expression "actual coal" presumably refers to this same initial or unit substance free from extraneous matter, such as ash, moisture and sulphur. The same idea is evidently intended in the quotation below, though the same qualification as to "actual coal" is not used, thus, "The results of our tests seem to indicate the interesting conclusion that the character of a coal seam, so far as its fuel value is concerned, is a nearly constant quantity over considerable areas. The determination of the value for seams would be of great use, as the rapid proximate analysis, or, for that matter, merely the determination of ash and moisture in low sulphur coals, would be sufficient to grade coals of the same vein. Of course, it is dangerous to argue from so few samples, but the proposition seems reasonable. At least, we hope that further work may confirm these conclusions."

Kent, in discussing this paper, in the same volume, page 946, says, "The conclusions of the authors that the 'actual' coal (moisture and ash excluded) of a given seam over considerable areas, may be regarded as of uniform heating value, is one of great practical importance. I have held the same opinion tentatively for a long time...."

Contemporaneous with the work of Lord and Haas was that of W. A. Noyes.² As a result of 21 calorimetric determinations on Indiana and Pittsburgh bituminous coals, he says, "The heating effect may be found, in all cases examined, with a maximum error of 2 per cent, by the following rule: Subtract from 100 the per cents of moisture, ash, and one half the per cent of sulphur, and multiply the remainder by 80.7. The product will be the heating effect of the coal burned to vapor of water, expressed in calories."

Whatever value may have attached to these propositions, the matter seems to have lain more or less dormant until the subject

¹Trans. Am. Inst. Min. Eng. 27; 259, 1898.

²Jour. Amer. Chem. Soc. 20; 285, 1898.

was brought again to the surface by Mr. A. Bement, who has in numerous articles insisted upon its great practical value, as, for example, referring to the advantage of having certain units of reference, he says, "The possibility of the more extended use of constants is presented and the author urges the feasibility of considering the pure coal compositions as constants for a coal seam or particular locality of such seams. This possibility has been suggested, principally by the fact that the heating power of the pure coal from a general locality does not vary over greater limits than that of the calorimetric method, and he has been able to employ it as a constant in calculating the heating power of dry and moist coal, having determined only moisture and ash, and obtained results that check with calorimetric determinations made on the same samples. The author, however, does not claim originality in this observation, but does insist that the use of such constants is of advantage. . . . This view concedes that coal from a certain locality or seam does not vary in quality, but that the variation is due to the presence of ash and moisture which are impurities associated with the coal."¹

In a subsequent paper,² he argues for the same constancy of values when referred to the pure coal basis. These considerations have, no doubt, led Mr. Bement and others to adopt the term "pure coal" as expressive of this idea of constancy in the "ash and water-free" substance, in addition to the fact of its being a more compact and convenient term to use.

In all of these discussions relating to the uniformity of values for the actual coal, it is evident that if there are any constituents that fail of recognition to the extent that they are not included among the factors for mineral or non-coal material, but on the contrary, are included in the actual coal substance, then the question arises as to whether we yet have a fair basis of reference for drawing conclusions as to the constancy or the degree of agreement which we may properly credit to the actual coal constituent.

¹Jour. Am. Chem. Soc. 28; 636.

²Jour. Western Society of Engineers 11; 757.

For example, the coals of the Mississippi Valley may have as high as 4 or even 8 per cent of sulphur. Indeed, variations of 1 to 3 per cent may be possible within the product from the same mine, especially where the washing of the coal is in vogue. Now if this variable is counted as part of the "actual coal," it by so much prohibits any uniformity of heat values being credited to this hypothetical substance we call "unit coal." This phase of the subject was touched upon in the discussion¹ accompanying the paper by Mr. Bement already mentioned. It was there urged that not only the sulphur, but certain volatile constituents were present which escaped determination as part of the ash, and were, therefore, included in the actual coal, thus introducing a variable which prevented accurate study of that substance. Shortly afterward, analytical evidence in support of this idea was developed by Mr. Wheeler,² and the results of his investigation were published in 1908. The essential point developed in that work was the evidence of the existence of a non-coal constituent which by the ordinary methods of analysis not only escapes recognition and measurement, but is counted as part of the true coal substance. This is the water of hydration or other volatile matter chemically combined with the mineral or ash substance in such a manner as to be driven off only at a red heat. For example, if the shale content of the ash has 8 per cent combined water, and the same is not counted with the ash but as part of the "volatile combustible," here is a variable which by so far keeps us from coming at the correct value for the actual or unit coal. Similar variables would accompany the presence of gypsum whose water of crystallization in the process of analysis would take its place as part of the pure coal substance. Calcium carbonate also would afford a similar variable in so far as it would lose carbon dioxide in the process of analysis. It should be noted here that Taylor and Brinsmaid have proposed a graphical method for arriving at unit coal values which, though empirical and consequently indi-

¹Parr; Jour. Western Society of Engineers 11; p. 762, 1906.

²Trans. Am. Inst. Min. Engs., Vol. 38, p. 621, 1908.

rect in character, is very ingeniously devised and no doubt is of much practical value.¹

III. EXPERIMENTAL DATA

It is the purpose of this paper to present the results of our own investigations, together with such applications as the data at hand will permit, in the hope that the facts presented may indicate the possibility of arriving directly at the determination of all of the non-coal or mineral constituents, including those more volatile mineral compounds which have heretofore been associated in analytical processes with the fuel. The fact should be especially emphasized that it has been the purpose of the investigation to arrive, first, at an exact determination of the inorganic component of the coal as distinct from the organic material, and, second, to study the constancy of composition of this organic substance as indicated by its heat content. Only in this manner can we arrive at a conclusion as to whether or not it has properties which will warrant its use as a fuel unit. Manifestly, therefore, the sulphur should be excluded from this unit. In so far as sulphur occurs in the form of iron pyrites, and this includes the major part, it is extraneous in character and bears no constant ratio to the amount of organic matter present.

For the purpose of illustrating by specific instances the effect of including such variable constituents as sulphur, etc., in the combustible matter, instead of in the ash, and so allowing them to augment falsely the actual coal substance, the following experimental procedure was followed:

A given sample of the coal was separated into two divisions of high and low ash content in a solution of zinc sulphate of 1.35 specific gravity, whereby that part of the coal with low ash and less pyrites was separated by floating from the heavier particles with higher ash and more sulphur, the latter sinking to the bottom. Now, upon the hypothesis that the "actual coal" in these

¹Jour. Ind. and Engrg. Chem. Vol. 1, Feb. 1909.

two divisions of the same sample should have the same heat value, the subjoined table is arranged to show what widely divergent values may be indicated by reason of different methods of arriving at the "actual coal" constituent. If everything excepting the ash as weighed and the moisture be credited to this material, there will result unit values, as shown under column (*a*) of the subjoined Table 1, which is the "pure coal" of Mr. Bement. If we take out the heat due to sulphur, and correct the remaining value for ash as determined, plus moisture, plus all of the sulphur, there will result values as shown in column (*b*), which would be the results as derived by means of the method of Lord and Haas. If we calculate the indicated values to the material as free from ash and moisture and correct also for one-half of the sulphur, there will result values, as shown under column (*c*), which would conform to the method as suggested by Dr. Noyes.

In column (*d*) we have results from the method of calculation which subtracts the heat due to the sulphur, corrects the ash for the sulphur, and also adds a uniform amount for hydration or volatile inorganic matter, amounting to 8 per cent calculated upon the corrected ash free from iron pyrites, assuming all of the sulphur to be in that form. A tabular statement, therefore, for these four different methods of calculation would be as follows:

(*a*) According to Bement

$$\begin{array}{r} \text{B. t. u. as indicated} \\ \hline 1.00 - (\text{Moisture} + \text{Ash as weighed}) \end{array}$$

(*b*) According to Lord and Haas

$$\begin{array}{r} \text{B. t. u.} - 4050 \text{ S} \\ \hline 1.00 - (\text{Moisture} + \text{Ash as weighed} + \text{Sulphur}) \end{array}$$

(*c*) According to Noyes

$$\begin{array}{r} \text{B. t. u. as indicated} \\ \hline 1.00 - (\text{Moisture} + \text{Ash as weighed} + 1/2 \text{ Sulphur}) \end{array}$$

(*d*) According to Parr and Wheeler

$$\begin{array}{r} \text{B. t. u.} - 5000 \text{ S} \\ \hline 1.00 - [\text{Moisture} + \text{Ash} + 5/8 \text{ S} + .08 (\text{Ash} - 10/8 \text{ S})] \end{array}$$

TABLE 1
COMPARATIVE VALUES OF "ACTUAL COAL"

Tab. No.	Lab. No.	DESCRIPTION OF SAMPLE	OVEN-DRY COAL				HEAT VALUE OF "ACTUAL COAL" AS CALCULATED BY DIFFERENT METHODS			
			Ash	Sul.	Iron	B. t. u.	(a) Non-coal as Ash only (uncorrected) Ref. to Indicated B. t. u.	(b) Non-coal as Ash (uncorrected) + Sulphur Ref. to B. t. u. — 4050 S.	(c) Non-coal as Ash + $\frac{1}{2}$ Sulphur Ref. to B. t. u. as Indicated	(d) Non-coal as 1.08 $\times$ Ash + 22/40 S. Ref. to B. t. u. — 5000 S.
1	6130 6131	Sangamon Co., Ill., Lump Coal:					Diff.	Diff.	Diff.	Diff.
		(a) Untreated.....	11.66	5.99	3.38	12356	13987	14709	14477	14331
		(b) Floated, Sp. Gr. less than 1.35.....	6.12	3.20	.65	13300	14164 + 177	14523 — 186	14412 — 65	14340 + 9
2	6122 6123	Sangamon Co., Ill., Screenings:								
		(a) Untreated.....	18.21	4.25	2.37	11478	14031	14709	14428	14442
		(b) Floated, Sp. Gr. Less than 1.35.....	8.13	2.95	.70	13043	14192 + 161	14534 — 175	14407 + 21	14392 — 50
3	6290 6121	Williamson Co., Ill., Washed Nut:								
		(a) Untreated.....	12.83	1.85	1.09	12523	14361	14593	14519	14603
		(b) Floated, Sp. Gr. less than 1.35.....	4.01	1.39	.54	13929	14509 + 148	14664 + 71	14615 + 96	14602 — 1
4	6129 6128	LaSalle Co., Ill., Washed Screenings:								
		(a) Untreated.....	10.05	3.43	2.32	12885	14316	14616	14602	14566
		(b) Floated, Sp. Gr. less than 1.35.....	3.94	2.33	1.29	13922	14487 + 171	14754 + 138	14680 + 78	14615 + 49

TABLE 1

COMPARATIVE VALUES OF "ACTUAL COAL"—(Continued)

Tab. No.	Lab. No.	DESCRIPTION OF SAMPLE	OVEN-DRY COAL				HEAT VALUE OF "ACTUAL COAL" AS CALCULATED BY DIFFERENT METHODS			
			Ash	Sul.	Iron	B. t. u.	(a) Non-coal as Ash only (uncorrected) Ref. to Indicated B. t. u.	(b) Non-coal as Ash (uncorrected) + Sulphur Ref. to B. t. u. — 4050 S.	(c) Non-coal as Ash + $\frac{1}{2}$ Sulphur Ref. to B. t. u. as Indicated	(d) Non-coal as $1.08 \times$ Ash + $22/40$ S. Ref. to B. t. u. — 5000 S.
5	6132	Vigo Co., Ind. Nut:								
	6133	(a) Untreated. (b) Floated, Sp. Gr. less than 1.35.....	16.84 4.27	7.62 3.08	5.17 1.06	11790 13870	14170 14478 + 308	15230 14836 — 394	14858 14725 — 133	14698 14638 — 60
6	6135	Sullivan Co., Ind. Lump:								
	6134	(a) Untreated. (b) Floated, Sp. Gr. less than 1.35.....	-6.11 2.53	3.37 1.29	2.24 .36	13664 14259	14551 14624 + 73	14944 14771 — 173	14819 14820 + 1	14741 14700 — 41
7		Franklin Co., Ill., Face sample:								
	471	(a) Sp. Gr. greater than 1.35.....	18.00	.57	Not Det.	11639	14194	14236	14244	14467
	463	(b) Sp. Gr. less than 1.35.....	4.64	.54		13765	14435 + 241	14492 + 229	14476 + 232	14513 + 46
8		Franklin Co., Ill., Face sample:								
	536	(a) Sp. Gr. greater than 1.35.....	14.43	1.45	"	12142	14190	14495	14310	14433
	464	(b) Sp. Gr. less than 1.35.....	3.83	.71	"	13918	14472 + 282	14550 + 60	14525 + 215	14541 + 108

TABLE 1

COMPARATIVE VALUES OF "ACTUAL COAL"—(Concluded)

Lab. No.	DESCRIPTION OF SAMPLE	OVEN-DRY COAL				HEAT VALUE OF "ACTUAL COAL" AS CALCULATED BY DIFFERENT METHODS			
		Ash	Sul.	Iron	B. t. u.	(a) Non-coal as Ash only (uncorrected) Ref. to B. t. u.	(b) Non-coal as Ash (uncorrected) + Sulphur Ref. to B. t. u. — 4050 S.	(c) Non-coal as Ash + $\frac{1}{2}$ Sulphur Ref. to B. t. u. as Indicated	(d) Non-coal as 1.08 $\times$ Ash + 22/40 S. Ref. to B. t. u. — 5000 S.
9	Perry Co., Ill., Face sample:					Diff.	Diff.	Diff.	Diff.
	(a) Sp. Gr. greater than 1.35.....	22.17	1.15	"	10922	14033	14183	14136	14405
465	(b) Sp. Gr. less than 1.35.....	4.22	.86	"	13763	14369 + 336	14464 + 281	14434 + 298	14446 + 41
10	Perry Co., Ill., Face sample:								
	(a) Sp. Gr. greater than 1.35.....	9.52	.65	"	12947	14309	14384	14360	14452
466	(b) Sp. Gr. less than 1.35.....	2.66	.74	"	13985	14367 + 58	14430 + 46	14422 + 62	14421 - 31
11	Williamson Co., Ill., Face sample:								
	(a) Sp. Gr. greater than 1.35.....	17.75	1.15	"	11766	14306	14451	14405	14599
467	(b) Sp. Gr. less than 1.35.....	4.08	.99	"	13942	14535 + 229	14644 + 193	14617 + 212	14615 + 16
12	Williamson Co., Ill., Face sample:								
	(a) Sp. Gr. greater than 1.35.....	18.28	1.37	"	11731	14355	14531	14475	14667
468	(b) Sp. Gr. less than 1.35.....	4.34	1.07	"	13970	14604 + 249	14725 + 194	14694 + 219	14690 + 23

The method of deriving a formula embodying the conditions prescribed under (*d*) would be as follows:

First, with reference to the subtraction of the heat due to the sulphur. It should be borne in mind that the purposes of this study are (1), to arrive at the actual weight of unit coal as represented by the expression 1.00 — (all non-coal constituents), and (2) to derive the actual heat per unit weight to be credited to this material, by dividing the indicated heat for this substance by the weight which produces it. Hence, for this particular purpose, the sulphur must be eliminated, both as to its heat value and as to its weight in the material whose value is sought for. This procedure may not suit the purpose of the engineer who has in mind only the available heat without reference to its source, but that is a matter quite apart from the facts which it is the purpose of this discussion to establish.

Second, the expression 5000 S has been used as indicating the heat due to the combustion of the sulphur, for the reason that the value 4050 S, as used in formula (*b*) represents the heat of combustion for pure sulphur, while the heat of combustion of sulphur in the form of pyrites, FeS_2 , combines also the heat of formation of iron oxide, Fe_2O_3 . It is the resultant value, therefore, of the several reactions involved that is desired.

According to the direct tests by Somermeier,¹ in the combustion of coal with known weight of iron pyrites, the indicated heat per gram of sulphur so combined is 4957 calories. In calculating heat values, the correction introduced for the combinations resulting from calorimeter reactions as compared with open-air combustion is 2042 calories per gram of pyritic sulphur; hence 4957 — 2042 or 2915 calories (5247 B. t. u.) represents the heat due to the burning of one gram of sulphur in pyritic form instead of 2250 calories (4050 B. t. u.), the amount which would be credited to sulphur in the free condition. A strict application of these values, therefore, would call for a correction of 5247 S, as representing the heat to be subtracted for the sulphur. This,

¹Jour. Am. Chem. Soc. Vol. 26, p. 566.

however, would imply that all of the sulphur is in the pyritic form. Since a certain portion of the sulphur is always present in organic or other form of less heat-producing capacity, it is deemed more nearly correct to use an even factor of 5000 as representing the heat to be credited to unit amounts of the total sulphur present.

The factors for the divisor in the formula under (*d*) are derived as follows:

The atomic ratio of iron to sulphur in iron pyrites (FeS_2) is 56 : 64; that is, $7/8$ of the total sulphur is the equivalent of the iron present as Fe.

The atomic ratio of the oxygen of the ash, combined as Fe_2O_3 to the total sulphur which it replaces is 48:128; that is, $3/8$ of the total sulphur is the equivalent of the oxygen present in the ash, combined as Fe_2O_3 , hence the ash as weighed may be corrected for the iron pyrites FeS_2 burned to Fe_2O_3 , by subtracting from the ash $10/8$ of the weight of the sulphur as determined. This remainder, therefore, is considered as the shaley and carbonate constituent upon which the 8 per cent of water of hydration, carbon dioxide, etc., are calculated. The expression for the total non-coal substance then becomes

$$\text{Non-coal} = \text{Moisture} + \text{Ash as weighed} + 5/8 \text{ S} + .08 (\text{Ash} - 10/8 \text{ S}).$$

Clearing of fractions and combining,

$$\text{Non-coal} = \text{Moisture} + 1.08 \text{ Ash} + 21/40 \text{ S}.$$

In this expression the factor $21/40 \text{ S}$ can not be further simplified by making it $1/2 \text{ S}$, for the reason that our correction for sulphur is already too small by that part of the organic sulphur not covered by the addition to the ash value of $3/8$ of the total sulphur indicated in the original formula. On the contrary, we shall be approaching nearer the truth by increasing slightly the sulphur correction, which may be done with convenience in calculating, by making this factor read $22/40 \text{ S}$ or $1/2 \text{ S} + 1/20 \text{ S}$.

Hence the simplification of the entire formula under (d) would be

B. t. u. or unit coal =

$$\frac{\text{Indicated B. t. u.} - 5000 \text{ S}}{1.00 - (\text{Moisture} + 1.08 \text{ Ash} + 1/2 \text{ S} + 1/20 \text{ S})}$$

Since the analytical values given in the table are based upon the coal as oven-dry, of course, the moisture factors in the above formula drop out, and would not enter into the calculations. In the table, for example, sample 1 has an indicated B. t. u. for the dry coal of 12 356. The calculations, therefore, for each column are

$$(a) = \frac{12356}{1.00 - .1166} = \dots\dots\dots 13\ 987$$

$$(b) = \frac{12356 - 4050 (.0599)}{1.00 - (.1166 + .0599)} = \dots\dots\dots 14\ 709$$

$$(c) = \frac{12356}{1.00 - (.1166 + .0299)} = \dots\dots\dots 14\ 477$$

$$(d) = \frac{12356 - 5000 (.0599)}{1.00 - [1.08 (.1166) + .02995 + .00299]} = \dots\dots\dots 14\ 331$$

From an examination of this table it seems evident that the values in columns (a), (b), and (c) vary for each pair of samples more widely than we should expect, provided our calculation in these cases is based upon the actual coal; the variation, for example, reaching nearly 2 1/2 per cent in No. 9. That a hydration component is the disturbing factor seems evident from the wide variation in the ash of the two divisions of this sample (22.17 per cent to 4.22 per cent), while the sulphur values are sufficiently close to eliminate any variable due to that element. In column (d), however, it is to be noted that the introduction of an amount of hydration equal to 8 per cent of the pyrite-free ash brings the two heat values to a variation of only 41 B. t. u. or less than 1/3 of 1 per cent. The component calling for this correction, therefore, seems to be directly associated with the ash, since the variation

in sulphur is too small to enter into the account. Equally striking evidence of the presence of such a component is seen in the samples numbered 7, 10, 11, and 12. Sample 8 is essentially the same as 7, and while there is not so close an agreement in this sample, still it must be recognized as confirmatory of the general proposition. If, for example, we admit a manipulation variant of 40 or 50 units, it is hardly to be expected that the other variables, such as the true amount of hydration or the exact character of the same, whether hydration of shale or carbonating of lime, may not carry with it an equal variable, so that in the present stage of our knowledge, it seems fair to consider even this variation quite within reasonable limits.

Another phase of these results is also to be noted. The agreement as to results just given above is seen to depend in large measure upon the correction of the high ashes in those samples referred to, by addition of a component which we have designated as hydration. Fortunately, the list of samples also includes coals high in sulphur, and this affords the necessary condition to show whether or not the sulphur enters into the proposition as a variable, and also what method of correction will most nearly neutralize its effect. Here, again, the close agreement, as in samples 1, 2, 4, 5, and 6, indicates that the method employed is correct in principle; that is, the heat value of the sulphur, taken as 5000 times the sulphur content, is subtracted from the indicated heat units, and the ash is restored as nearly as is conveniently possible, to include the sulphur as joined to the iron in its original or pyritic form. It is realized, as already indicated, that an error is inherent in this procedure, if that part of the sulphur is present as organically combined. Strictly considered, therefore, it should not be reckoned as pyritic sulphur. Test has been made, however, of introducing a further refinement into the calculation by separating the sulphur into the organic part and the inorganic, the amount of the latter being indicated by the content of iron present in the ash. The iron pyrites thus calculated, Table 2, on this iron basis has been

made a part of the original non-coal substance. The 8 per cent of hydration, etc., has then been calculated to the ash as corrected for this amount of pyrites burned to oxide, and finally the organic sulphur has been added as a part of the non-coal matter. The indicated heat units were diminished by the total heat to be credited to the sulphur, taking account of its two forms as indicated in the formula for column (e), thus

(e) =

$$\frac{\text{B. t. u.} - [5247 \times 8/7 \text{ Fe} + 4050 \times (\text{S} - 8/7 \text{ Fe})]}{1.00 - [\text{Moisture} + \text{Ash} + 5/7 \text{ Fe} + .08 (\text{Ash} - 10/7 \text{ Fe}) + (\text{S} - 7/8 \text{ Fe})]}$$

In this formula, the iron weighed as Fe_2O_3 has a ratio of oxygen to iron of 48 : 112 or 3/7. To restore it to an equivalent of FeS_2 which has a ratio of S (64) to Fe (56) or 8 : 7 would require the addition to the ash content of 5/7 of the iron as determined. Similarly 8/7 of the iron value represents the sulphur as originally joined to the iron in the pyritic form, and 10/7 of the iron represents the Fe_2O_3 as a component part of the ash as weighed.

Since the analytical values refer to the coal on the dry basis, the factor for moisture drops out of the formula. The results of this method of calculating are given for the first six samples in column (e) of Table 2, placed in comparison with column (d) repeated from the previous table. As may be readily seen, the relative values are in substantially the same agreement as before. This method involves the added requirement of an iron determination and does not altogether remove the uncertainty as to the form in which the combinations of sulphur occur. In the present state of our knowledge, as well as on the score of practicality, we seem to be justified in accepting the values and formula as given in column (d).

The arguments thus far brought forward to prove the correctness of the method for arriving at the real weight of non-coal substance are sufficiently conclusive for the twelve samples included in the table. How generally applicable this method will be for all types and all regions, remains for the subsequent part of this paper to discuss.

TABLE 2

COMPARATIVE VALUES OF "ACTUAL COAL"

Tab. No.	Lab. No.	DESCRIPTION OF SAMPLE	OVEN-DRY COAL				(d)	(e)
			Ash	Sul- phur	Iron	B. t. u.		
1	6130	Sangamon Co., Ill., Lump Coal: (a) Untreated..... (b) Floated, Sp. Gr. less than 1.35.....	11.66	5.99	3.38	12356	Diff. 14331 + 9	Non-coal as Ash, Water, Pyritic Sulphur, Organic Sulphur and 8% Ash as Corrected for Actual Fe ₂ O ₃ 14494 14536
2	6131		6.12	3.20	.65	13300		
3	6122	Sangamon Co., Ill., Screenings: (a) Untreated..... (b) Floated, Sp. Gr. less than 1.35.....	18.21	4.25	2.37	11478	Diff. 14442 - 50	14569 14567 - 2
4	6123		8.13	2.95	.70	13043		
5	6290	Williamson Co., Ill., Washed Nut: (a) Untreated..... (b) Floated, Sp. Gr. less than 1.35.....	12.83	1.85	1.09	12523	Diff. 14603 - 1	14605 14659 + 54
6	6121		4.01	1.39	.54	13929		
7	6129	LaSalle Co., Ill., Washed Screenings: (a) Untreated..... (b) Floated, Sp. Gr. less than 1.35.....	10.05	3.43	2.32	12885	Diff. 14566 + 49	14620 14680 + 60
8	6128		3.94	2.33	1.29	13922		
9	6132	Vigo Co., Ind., Nut: (a) Untreated..... (b) Floated, Sp. Gr. less than 1.35.....	16.84	7.62	5.17	11790	Diff. 14698 - 60	14779 14783 + 4
10	6133		4.27	3.08	1.06	13870		
11	6135	Sullivan Co., Ind., Lump: (a) Untreated..... (b) Floated, Sp. Gr. less than 1.35.....	6.11	3.37	2.24	13664	Diff. 14741 - 41	14833 14770 - 63
12	6134		2.53	1.29	.36	14259		

As a possible source of variation, the different layers of the same seam were studied with a view to determining inherent variations in the stratification of the coal, which, by variations in sampling or mining, might enter into the case and to a certain extent, modify the fact of uniformity. Three mines were, therefore, sampled with reference to the top, middle, and bottom layers of coal, or with reference to certain zones or bands of coal that seemed to have a structure more or less characteristic and distinct from the other layers. These results are listed in the following table, the basis of comparison being the thermal units calculated to "unit coal," which in subsequent discussion, as already indicated, will be the term made use of in this paper for that coal free from ash, moisture, pyrites, and volatile inorganic matter, as calculated under column (*d*) in Tables 1 and 2.

Attention is called to the following points. In the Collinsville sample, the bands of division were approximately the upper 2 feet, the lower 2 feet, and the middle zone of about 4 feet. When referred to the "unit coal" basis, the upper and middle divisions are in close agreement. The lower layer is considerably higher. This fact would have a modifying influence on the entire face of the seam as is illustrated in No. 4, which is a calculated composite value based on the factors for samples No. 1, 2 and 3. No. 5 and 6 are samples taken from the entire face of the seam, and taken from a mine located not over 2 or 3 miles from the mine from which the first samples by layers were taken. It is evident that the values indicated for the separate layers are not variable to an extent which would noticeably change the ultimate value for the entire face. Moreover, in the process of mining, the output represents the face of the vein and not the various layers. However, the facts brought out in this comparison of the various strata are valuable as indicating certain variations in composition of the same seam which might result from changes in the relative thickness of certain bands. In the same region, or in the same vein, these possible variations due to this phase of the matter would seem to be practically negligible when we consider

the regular output of the mine, since a mixture of the entire seam is inevitable, and these small variations of the layers would be very easily neutralized.

The same statement is applicable to the results as shown for the two additional sections similarly examined from Belleville

TABLE 3

VARIATIONS IN THE CALORIFIC VALUE OF THE "UNIT COAL" FOR DIFFERENT HORIZONTAL LAYERS OF THE SEAM

Tab. No.	Lab. No.	DESCRIPTION OF SAMPLE	OVEN-DRY COAL			Non-coal as 1.08 Ash + 22/40 S. Ref. to B. t. u. — 5000S.
			Ash	Sul-phur	B. t. u.	
COLLINSVILLE, ILLINOIS						
1	725c	Top 23 in.	6.14	4.44	13505	14606
2	725b	Middle 48 in.	12.02	3.84	12618	14634
3	725a	Bottom 22 in.	14.86	7.52	12297	14936
4	725	Calculated for entire face 93 in.	11.22	4.85	12762	14694
5	723	Sample taken from entire face.	12.23	4.37	12604	14675
6	724	Sample taken from entire face.	9.69	3.33	12982	14613
BELLEVILLE, ILLINOIS						
1	1000	Top 4 in.	6.75	3.35	13629	14814
2	999	$\frac{1}{4}$ in.; 2 in. from the top.	2.09	2.66	14255	14667
3	995	Entire face, 76— $\frac{1}{2}$ in.	12.47	4.19	12587	14694
DUQUOIN, ILLINOIS						
1	422	Top 30 in.	6.13	.76	13573	14560
2	421	Bottom 69 in.	14.71	.98	12181	14516
3	....	Entire face. 99 in.	12.11	.91	12603	14531

and Duquoin. The agreement is even more marked than in the case of the Collinsville seam.

Notwithstanding these evidences of uniformity, the fact should not be lost sight of that these results have a special value in that they show at a glance the necessity of care in taking face samples, to see that the cut is made equally and from the entire working face of the seam. It is evident also that lump or hand samples which are frequently taken for analysis are not only of

little value but are as a rule positively misleading, and the error is quite as likely to be of a minus as of a plus character.

IV. ASH COMPOSITION

Notwithstanding the very satisfactory indication of the adaptability of the proposed formula for arriving at the unit coal values, as shown by the foregoing Tables 1 and 2, the question still remains as to whether the samples chosen are sufficiently typical to represent all the varieties of composition so far as the ash or inorganic content is concerned. Under this division of the subject, therefore, is taken up a study of this phase of the matter. As a first step, it was deemed necessary to make an analysis of the ash of the coals selected for use in the above tables. For example, the somewhat arbitrary factor, 8 per cent, has been adopted as covering a constant amount of volatile inorganic constituent to be reckoned with the total ash. It may make an appreciable difference whether this component is present as water of hydration, as in a clay or shale, or combined with lime as carbon dioxide. If in the latter combination, the amount of lime present would be an indication of that fact, while the amount of alumina present might serve to indicate the likelihood of this percentage being represented by hydration of shale or clay. An analysis of the ash of the 12 samples as listed in Table 2 is given in Table 4.

In this table, attention is first called to the fact that, with the exception of sample 3, the amount of lime is quite uniform. Here the lime approximates 12 per cent. By reference to the column for alumina, which might be taken as an indication of the clayey matter present, a very fair uniformity also exists, with the possible exception of sample 11, where the aluminium content is relatively low. Now, turning to Table 2 for an indication of a variation in the calculated values for unit coal, it does not seem that these variations in samples No. 3 and No. 11 have entered into the case in an appreciable degree.

Thus far it might be safe to conclude, that the adoption of

the 8 per cent constant, as representing the volatile matter of the ash, is applicable. However, if in this group we have a variation in the lime content from 2 to 12 per cent, as in samples 7 and 3, have we any evidence that it stops there? Similarly,

TABLE 4
ASH COMPOSITION OF COALS OF TABLE 2

Tab. No.	Lab. No.	DESCRIPTION	Ash in Dry Coal %	ANALYSIS OF ASH Per Cent				
				SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	CaO	MgO
1	6130	Sangamon Co., Ill., Lump.	11.66	33.1	42.5	17.9	5.6	0.9
2	6131	Sangamon Co., Ill., Lump.	6.12	54.2	16.4	24.2	4.1	1.2
3	6122	Sangamon Co., Ill., Screenings.....	18.21	49.2	20.7	17.1	11.9	1.1
4	6123	Sangamon Co., Ill., Screenings.....	8.13	55.9	13.0	23.6	6.7	0.8
5	6290	Williamson Co., Ill., Washed Nut.....	12.83	54.1	12.1	23.8	6.7	1.2
6	6121	Williamson Co., Ill., Washed Nut.....	4.01	51.7	19.3	24.6	2.4	1.0
7	6129	La Salle Co., Ill., Washed Screenings.....	10.05	40.3	34.0	22.8	2.0	0.9
8	6128	La Salle Co., Ill., Washed Screenings.....	3.94	.....	.....	.....	.....	.....
9	6132	Vigo Co., Ind., Nut.....	16.84	32.9	43.8	20.5	2.9	0.9
10	6133	Vigo Co., Ind., Nut.....	4.27	35.1	35.6	25.3	2.3	0.6
11	6135	Sullivan Co., Ind., Lump..	6.11	27.1	52.3	14.1	4.4	1.2
12	6134	Sullivan Co., Ind., Lump..	2.53	45.8	20.2	28.3	5.4	0.0

if the alumina may drop from 25 per cent (No. 10) to 14 per cent (No. 11), can we conclude that these numbers represent the limits of variation, and, if not, will greater variations in these factors cause a disturbance in the factor chosen to represent the volatile matter present?

In extending our study over a wider range of ash analysis, we soon come upon cases where much higher percentages of lime are in evidence. In view of this fact, it was considered worth while to estimate also the carbon dioxide and the chlorine. The carbon dioxide would be a more direct index of volatile loss of ash than the content of lime, since the latter might be combined in other than carbonate form. Chlorine, if present in any form,

would be volatile, depending on the temperature made use of. Table 5 is given as illustrating the extremes to which lime as calcium carbonate, and alumina combined as clayey matter may be met, at least in the ash from Illinois coals.

TABLE 5
ASH COMPOSITION OF COALS WITH HIGH PERCENTAGE OF LIME

Tab. No.	Lab. No.	DESCRIPTION	In per cent of Dry Coal			ANALYSIS OF ASH				
			Ash	CO ₂	Cl	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	CaO	MgO
1	734	Grundy Co., Ill.....	5.82	.88	none	22.8	32.4	10.2	34.0	0.7
2	1095	Saline Co., Ill.	11.49	1.22	.04	32.7	33.0	9.0	25.3	0.8
3	1178	Clinton Co., Ill.....	15.56	2.48	.10	39.0	22.4	6.3	31.7	0.7
4	1403	Peoria Co., Ill.....	15.46	2.48	none	25.7	12.9	6.8	54.5	1.5

It might be argued from the results in Table 5, that whereas the lime content is high, the alumina is low, and there is, therefore, a compensation which would still furnish evidence that the 8 per cent constant for the inorganic volatile matter would be applicable. However, to test the matter, it was deemed advisable to subject these samples to the floating test as already indicated, giving as a result two divisions of each sample, one with an abnormally low ash, the other with an abnormally high ash; the latter division in each case still further accentuating the lime factor. In consequence of this division, the analysis of the eight resulting samples together with the calorific values is presented in Table 6. Columns (a) and (d) only are given in order that a comparison may be made between the ash values for "ash and water-free" or "pure coal" with the "unit coal" values as derived by the formula already made use of on page 14.

From the calculations under column (a) and column (d), it is evident that the wide discrepancies under column (a) are due to a failure to take into consideration those mineral constit-

units of the coal which properly belong to the ash. This is the fuel unit designated the "ash and water-free," combustible or "pure coal" basis adopted by engineers. Under column (d), the

TABLE 6

PROXIMATE ANALYSIS WITH CALORIFIC VALUES FOR FLOAT AND SINK COAL WITH HIGH PERCENTAGES OF LIME IN THE ASH

Tab. No.	Lab. No.	DESCRIPTION	In per cent of Dry Coal			Heat Value of "Actual Coal" as Calculated by Different Methods	
						(a)	(d)
			Ash	Sul.	B. t. u.	"Pure Coal" Basis	"Unit Coal" Basis
						B. t. u. 1.00 — Ash	B. t. u. — 5000S. 1.00 — (1.08 Ash + $\frac{22}{40}$ S.)
1	734	Float, Grundy Co.	4.57	1.44	13475	14120	Diff.
2	734	Sink, Grundy Co.	21.99	5.00	10733	13760	Diff.
3	1095	Float, Saline Co.	6.42	2.65	13663	14600	+ 45
4	1095	Sink, Saline Co.	19.94	7.01	11122	13902	+ 138
5	1178	Float, Clinton Co.	8.54	1.96	12634	13813	— 321
6	1178	Sink, Clinton Co.	31.90	3.75	8856	13004	— 321
7	1403	Float, Peoria Co.	10.37	2.39	12796	14276	14489
8	1403	Sink, Peoria Co.	34.24	4.71	9216	14014	14859
						— 262	+ 370

unit coal values come very much closer together, but are not in such satisfactory agreement as was the case with the coals in Table 2, having a low lime content in the ash. It is evident, therefore, that in these two extreme divisions which have been made by the process of floating out to get the lighter and sinking the heavier ash coal, the inorganic volatile matter must be accounted for in some further correction than would be included in the 8 per cent adopted in calculation for Table 2. It is evident in this set of samples, that we have accentuated in an extreme manner the effect of a high ratio of carbonate of lime, bringing this constituent up to 16.67 per cent of the total coal in No. 5 of

the table, and to 11.99 per cent in No. 6. While these percentages are abnormal, they serve well the purpose of indicating the effect upon the proposed formula for arriving at unit coal values. The first question which presents itself, therefore, is whether we should not correct our ash factor, not by an 8 per cent addition alone, but by adding directly to the ash as weighed, the amount of carbon dioxide present, on the assumption that all of the calcium carbonate would be decomposed, setting free the CO_2 . This involves another hypothesis, namely, that in the ordinary determination of ash, the calcium carbonate present is completely decomposed. To test this point, the four samples, subdivided into pairs of low and high ash each, were subjected first to the ordinary ash determination as directed by the Committee of the American Chemical Society on standard methods for coal analysis. No important modification of this method was employed. After complete burning off of the carbon in a porcelain crucible over a Bunsen lamp, a blast lamp, driven at moderate intensity, was applied for 30 to 40 minutes. The results are listed in Table 7, in the first column for ash percentages, marked (*a*). In the column marked (*b*), the method employed made use of a platinum crucible and after burning off the carbon, an intense heat was applied by means of the blast lamp, continuing the blasting to constant weight. As will be seen from these results, a very wide difference may be made in the seemingly simple matter of determining the ash. Evidently under column (*a*) only a part of the calcium carbonate has been decomposed in the "sink" samples.

In this table, therefore, we have a striking illustration of the variations that may enter into the ash determination. The evidence of a variable element indicated its presence in a very marked manner in the process of obtaining the values for column (*a*). It was found almost impossible to secure duplicate results, the values sometimes varying in the two portions run in parallel by as much as 1.00 per cent. This evidence of a high content of calcium carbonate and its effect on the accuracy of the ash deter-

TABLE 7

VARIATIONS IN ASH VALUES WHERE CALCIUM CARBONATE IS A CONSTITUENT OF THE COAL

Tab. No.	Lab. No.	DESCRIPTION	(a)	(b)	Difference in per cent of Dry Coal
			Ash as Determined by Usual Method	Ash as Determined by Blasting to Constant Wgt and Fusion	
1	734	Float, Grundy Co., Ill.	4.57	3.54	1.03
2	734	Sink, Grundy Co., Ill. . .	21.99	16.85	5.14
3	1095	Float, Saline Co., Ill. . . .	6.42	5.96	0.46
4	1095	Sink, Saline Co., Ill. . . .	19.94	18.59	1.35
5	1178	Float, Clinton Co., Ill. . .	8.54	7.23	1.31
6	1178	Sink, Clinton Co., Ill. . .	31.90	26.88	5.02
7	1403	Float, Peoria Co., Ill. . .	10.37	9.08	1.29
8	1403	Sink, Peoria Co., Ill. . . .	34.24	22.93	11.31

mination is of far-reaching importance. It affects in a very material manner any method of reference to a unit of combustible, especially such as is made use of by the engineering profession under the designation of "ash and moisture-free" material. It also seriously affects those results in a coal analysis which are obtained indirectly by difference. For example, the value for fixed carbon is thus estimated. Any error in the ash determination is therefore loaded upon this constituent. An equally erroneous feature accompanies the ultimate analysis where the total carbon is measured as CO_2 . The carbon dioxide combined with the calcium oxide in the coal is thus made to appear in the final result as augmenting the value for total carbon. But it is not the purpose here to discuss the effect of this possible source of error. The immediate problem in hand is to arrive at the actual non-coal or inorganic substance as an essential factor in calculating the values for unit coal. The obvious suggestion, therefore, would be to make a determination of all possible volatile constituents, especially the CO_2 and Cl and augment the ash values found at the higher temperature by these percentages. Such an analysis was made, as shown in Table 8. A complete

analysis was also made showing all the mineral constituents, so that any bearing these factors might have, could be studied simultaneously with the question of the true ash or inorganic matter.

In considering the probable reactions of the ash at a fusion temperature, it would be conceded at once that all of the CO_2 would be driven off. This, therefore, would be the first increment to add to the ash as above determined. Similarly, the chlorine present would be driven off. Evidently, in these particular samples, the larger portion of the chlorine is combined as CaCl_2 , which was not washed out of the texture of the coal after being subjected to the floating process in a CaCl_2 solution. But whether joined as NaCl or CaCl_2 , it is probable that the ultimate result is the formation of silicates of sodium and calcium with liberation of chlorine. Hence it seems proper to add a second increment to the ash values, that of the chlorine percentages. When we come to a disposition of the SO_3 value, the case is not so clear. Ordinarily, it should be noted, the amount of sulphate present in a coal is so small as to be negligible, but it so happens that the samples selected for this particular series had been in laboratory storage for over a year, with the result, that when the ultimate constituents were all sought out, quite an appreciable amount of sulphate of iron had formed. Now the decomposition of this material is easily effected at a temperature above 300° . Hence the indication would seem to be that a further correction for the ash content should be made by adding the percentage found for this constituent. However, it should be borne in mind that calcium carbonate is present in sufficient quantity to take care of this SO_3 by formation of $\text{CaSO}_4 + \text{CO}_2$. By testing artificial mixtures of calcium carbonate and ferrous sulphate, with and without the addition of organic matter, the residual fusion showed sufficient sulphate remaining as CaSO_4 to warrant the conclusion that no correction should be made for the SO_3 found to be present in the original coal.

In view of these facts, therefore, the calculation for the unit

TABLE 8—ASH COMPOSITION—IN PER CENT OF DRY COAL

Tab. No.	Lab. No.	Description	Ash by Blasting to Constant Weight and Fusion in Pt. Cruc.	SiO ₂	Fe ₂ O ₃ Al ₂ O ₃	CaO MgO	Na	Cl	SO ₃	CO ₂	Total S	B. t. u.
1	734	Float.....	3.54	.98	1.71	.85	.12	1.00	.43	.10	1.44	13475
2	734	Sink.....	16.85	2.44	7.91	6.50	.31	1.15	1.05	3.68	5.00	10733
3	1095	Float.....	5.96	2.93	2.63	.40	.07	.17	.22	.13	2.65	13663
4	1095	Sink.....	18.59	5.23	9.48	3.88	...	.31	.81	2.38	7.01	11122
5	1178	Float.....	7.23	3.33	3.02	.88	.23	1.41	.20	.21	1.96	12634
6	1178	Sink.....	26.88	9.03	9.49	8.36	.27	1.20	.56	5.27	3.75	8856
7	1403	Float.....	9.08	5.46	2.33	1.29	.22	1.07	.23	.31	2.39	12796
8	1403	Sink.....	22.93	5.64	7.09	10.20	.19	1.17	.99	7.35	4.71	9216

TABLE 9—"UNIT COAL" IN SAMPLES WITH HIGH CALCIUM CARBONATE

Tab. No.	Lab. No.	Description	IN PER CENT OF DRY COAL				"PURE COAL"		"UNIT COAL"	
			Ash as Determined by High Fusion to Constant Weight	CO ₂	Cl	B. t. u.	B. t. u. 1.00 - Ash	B. t. u. - 5000S 1.00 - (1.08 Ash (corr.) + ²² / ₄₀ S.)	Diff.	
1	734	Float.....	3.54	.10	1.00	13475	13969	14219	14219	
2	734	Sink.....	16.85	3.68	1.15	10733	12908	14214	14214	5
3	1095	Float.....	5.96	.13	.17	13663	14528	14742	14742	
4	1095	Sink.....	18.59	2.38	.31	11122	13662	14736	14736	6
5	1178	Float.....	7.23	.21	1.41	12634	13618	14030	14030	
6	1178	Sink.....	26.88	5.27	1.20	8856	12111	14009	14009	21
7	1403	Float.....	9.08	.37	1.07	12796	14073	14508	14508	
8	1403	Sink.....	22.93	7.35	1.17	9216	11941	14172	14172	336

coal values on these samples was based on an ash content in which the ash as weighed had been subjected to a very high temperature in a platinum crucible, and continued until a constant weight was secured, and the ash fused; to this was added the CO_2 present in the dry coal, and also the factor for chlorine. The formula already given, therefore, was simply modified by the above conditions, and would be expressed as follows:

$$\text{Unit Coal} = \frac{\text{Indicated B. t. u.} - 5000 \text{ S}}{1.00 - [(\text{Ash} + \text{CO}_2 + \text{Cl}) \times 1.08 + 22/40 \text{ S}]}$$

The results of this calculation are given in Table 9, with a comparison wherein the values are calculated to "pure coal" or the "ash and water-free" basis and to the "unit coal" with the ash corrected for the CO_2 and Cl present.

Concerning these results, the proposed correction of the ash by addition of the CO_2 and Cl would seem to meet the conditions as indicated by the close agreement of the "unit coal" values. The last sample, No. 8 of the table, is not in so good agreement as could be wished. The only explanation to be suggested at the present time is that the very high per cent of calcium carbonate, 16.67 per cent, would seem to require that a correction be made in the calorimetric value to allow for the heat of decomposition required to separate that amount of calcium carbonate into its constituent parts. This would mean that 786.6×16.67 per cent or 131 B. t. u. would represent the heat of dissociation for the calcium carbonate present. This amount, added to the indicated heat, would represent the total heat developed in the combustion as 9112 B. t. u. This amount introduced into the formula would show 14 383 B. t. u. as the unit coal value, or a difference from the low ash sample of 112 units instead of 336 as in the table. More study of this extreme type of coal must be made, and upon fresh samples with the sulphate constituent eliminated, before a final judgment can be formulated as to the adaptability of the formula to such cases. The remarkable conformity of the values in three of the four cases would seem to

argue strongly in favor of the corrections for CO_2 and Cl as covering the case. In consideration of the facts set forth, therefore, in these last tables, it was deemed necessary to make an extended inspection of the coals of the State with special reference to their content of carbonate and chlorine. About sixty samples were selected and in addition to the usual ash determination, analysis

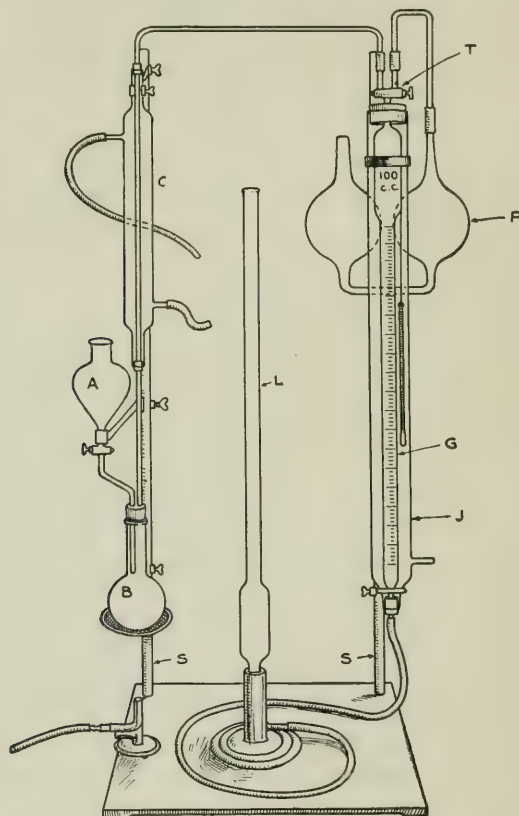


FIG. 1 APPARATUS FOR DETERMINING CO_2

was made of the ash constituent, namely, silicon, iron, alumina, lime, and magnesia. In addition, a determination was made of the chlorine and carbonate present. The chlorine was determined by digesting 2 grams of the pulverized coal on a steam

bath with about 200 cc. of water, filtering, making up to 500 cc., and titrating an aliquot part with standard silver nitrate solution.

The carbonate was determined by weighing out 5 grams of coal and treating with acid in the apparatus designed for such work as shown in Fig. 1. This is an improved form of the apparatus described in Bulletin 7 of the Engineering Experiment Station, for the volumetric estimation of carbon dioxide, by absorbing the same in a pipette, as *P* of the figure, and measuring the contraction in the jacketed burette.

From the values thus obtained for these two constituents, it will be seen from the table that the high amounts of both are distributed quite irregularly throughout the State, and very frequently in a sufficiently high amount to make the introduction of their values into any careful analytical work on such coals an essential feature, if trustworthy results are to be forthcoming.

An answer is thus afforded, in such cases at least, to the query of the Committee of the American Chemical Society on Coal Analysis¹: "Are carbonates likely to be present in the ash in such amount that heating over a blast lamp would lessen the weight appreciably?" An affirmative answer is also indicated in Table 7, where the weight of ash is lessened on blasting by 11.31 per cent of the coal, as in sample 8.

A further suggestion results from these frequent indications of carbon dioxide. The high carbonate content is accompanied by a high lime factor and the question at once occurs as to whether this factor for CO_2 might not serve as an index of fusibility of the ash quite as accurately as the content of sulphur, since high lime is as promotive of slagging as iron. Numerous tests on the fusibility of ash have confirmed this idea. It is hoped that this matter of the fusibility of coal ash may be taken up for further study in the near future.

¹Jour. Am. Chem. Soc. Vol. 20, p. 284, 1898.

TABLE 10

ANALYSIS OF COAL ASH

(Including Values for CO₂ and Cl)

Tab. No.	Lab. No.	DESCRIPTION	Ash and Volatile Inorganic Matter DRY COAL Per Cent		MINERAL CONSTITUENTS OF ASH AS OBTAINED BY HIGH FUSION Per Cent						
			Ash by Usual Method	Seam No.	CO ₂	Cl	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	CaO	MgO
1	733	S. Wilmington, Grundy Co.....	8.17	2	.15	None	28.8	41.1	22.5	7.0	.6
2	734	Coal City, Grundy Co.....	5.82	2	.88	"	22.8	32.4	10.2	34.0	.7
3	1411	Hollis, Peoria Co.....	10.90	2	.98	.27	33.3	41.8	10.2	16.6	.7
4	896	Spillerton, Williamson Co.....	10.68	5	.70	.31	43.2	37.9	12.5	3.9	.5
5	1092	Equality, Gallatin Co.....	10.85	5	.72	None	39.5	29.6	8.5	23.8	1.0
6	1094	Eldorado, Saline Co.....	10.54	5	.26	.15	42.8	38.3	9.3	8.3	1.3
7	1095	Eldorado, Saline Co.....	11.49	5	1.22	.04	32.7	33.0	9.0	25.3	.8
8	1110	Eldorado, Saline Co.....	12.68	5	.51	.14	30.6	49.7	7.3	13.0	.8
9	1112	Harrisburg, Saline Co.....	8.99	5	.11	None	48.7	26.1	22.5	3.2	1.2
10	1115	Ledford, Saline Co.....	11.58	5	.34	"	40.0	26.4	21.8	9.3	1.1
11	1116	Ledford, Saline Co.....	9.89	5	1.51	.05	29.4	20.0	20.3	26.5	2.0
12	540	Springfield, Sangamon Co.....	10.76	5	.32	.08	40.5	37.0	8.2	11.8	.5
13	720	Lincoln, Sangamon Co.....	13.81	5	.54	.32	35.1	22.4	10.2	30.8	1.5
14	740	Springfield, Sangamon Co.....	12.75	5	.34	None	56.4	14.9	18.4	9.1	1.2
15	741	Springfield, Sangamon Co.....	12.47	5	.85	.24	43.3	24.1	9.0	19.9	1.2
16	1403	Bartonville, Peoria Co.....	15.46	5	2.48	None	25.7	12.9	6.8	54.5	1.3
17	1404	Canton, Fulton Co.....	12.52	5	1.30	"	43.9	20.1	12.3	22.4	1.3
18	1407	Edwards Sta., Peoria Co.....	16.25	5	2.15	.03	33.1	30.6	3.2	31.1	.8
19	1410	Maxwell, Peoria Co.....	14.78	5	1.57	None	34.3	24.8	8.1	31.3	.7
20	1412	E. Peoria, Tazewell Co.....	.....	5	.61	.19	45.0	26.3	11.6	16.1	1.0
21	1413	Pekin, Tazewell Co.....	.....	5	1.36	None	43.0	17.7	6.6	31.6	1.0

TABLE 10

ANALYSIS OF COAL ASH

(Including Values for CO₂ and Cl)—(Continued)

Tab. No.	Lab. No.	DESCRIPTION	Ash and Volatile Inorganic Matter Dry Coal Per Cent		MINERAL CONSTITUENTS OF ASH AS OBTAINED BY HIGH FUSION						
			Per Cent		Per Cent						
			LOCATION	Seam No.	Ash by Usual Method	CO ₂	Cl	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	CaO	MgO
22	557	Westville, Vermilion Co.	6	9.15	1.08	.15	47.9	26.9	18.5	5.6	1.1
23	558	Westville, Vermilion Co.	6	8.03	.47	.15	52.9	23.8	5.8	17.1	.3
24	722	Thayer, Sangamon Co.	6	11.04	.19	.23	44.0	32.0	13.2	9.8	1.0
25	725a	Collinsville, St. Clair Co.	6	11.22	.70	None	50.9	17.3	19.5	11.8	.6
26	725b	Collinsville, St. Clair Co.	6	.....	.72	"	48.2	18.2	21.3	11.0	1.3
27	725c	Collinsville, St. Clair Co.	6	.....	.37	"	33.6	27.2	11.4	16.8	1.2
28	735	Mt. Olive, Macoupin Co.	6	10.86	.36	.16	40.7	32.5	17.0	9.8	.8
29	736	Mt. Olive, Macoupin Co.	6	11.40	.13	.22	49.1	32.2	13.5	4.5	1.4
30	991	Belleville, St. Clair Co.	6	15.80	.....	.....	44.8	20.3	18.6	16.4	1.5
31	996	Germanatown, Clinton Co.	6	10.47	.44	.23	38.8	27.5	19.4	13.2	1.1
32	1001	Lebanon, St. Clair Co.	6	12.53	.65	.12	52.9	16.7	17.3	11.8	1.3
33	1002	O'Fallon, St. Clair Co.	6	13.43	.50	.16	44.3	28.4	13.2	11.5	1.3
34	1003	S. W. of O'Fallon, St. Clair Co.	6	12.94	.76	None	44.4	19.3	20.8	16.1	1.1
35	1117	Donkville, Madison Co.	6	10.59	.64	None	40.8	27.4	13.2	16.9	1.6
36	1118	Troy, Madison Co.	6	13.65	.55	.05	44.8	19.2	21.2	11.2	1.1
37	1119	Maryville, Madison Co.	6	11.72	.71	.09	45.6	27.0	5.8	20.8	.8
38	1176	Breese, Clinton Co.	6	15.59	.40	.33	55.5	21.4	5.9	16.4	.8
39	1178	Trenton, Clinton Co.	6	15.56	2.48	.10	39.0	22.4	6.3	31.7	.7
40	419	Zeigler, Franklin Co.	7	10.11	.37	.50	59.0	3.1	31.0	5.6	1.3
41	420	Zeigler, Franklin Co.	7	7.53	.21	.55	54.3	9.0	29.1	6.3	1.3
42	421	DuQuoin, Perry Co.	7	14.71	.65	.42	55.2	8.3	26.6	7.3	1.3

TABLE 10

ANALYSIS OF COAL ASH

(Including Values for CO₂ and Cl)—(Concluded)

Tab. No.		Lab. No.	DESCRIPTION		Ash and Volatile Inorganic Matter DRY COAL Per Cent		MINERAL CONSTITUENTS OF ASH AS OBTAINED BY HIGH FUSION					
							Per Cent					
							LOCATION		Ash by Usual Method	CO ₂	Cl	SiO ₂	Fe_{2}O_{3}	Al_{2}O_{3}	CaO	MgO
43	422	DuQuoin, Perry Co.	7	.28	.47	53.9	7.8	28.0	6.7	1.0		
44	459	Herrin, Williamson Co.	7	.12	.13	59.9	8.1	29.4	1.9	1.0		
45	460	Herrin, Williamson Co.	7	.47	.12	56.1	8.1	27.2	5.4	.9		
46	461	Sesser, Franklin Co.	7	.28	.56	51.4	10.2	31.5	5.7	1.1		
47	462	Marion, Williamson Co.	7	.14	None	50.1	20.0	26.2	2.9	.8		
48	1088	Herrin, Williamson Co.	7	.35	"	46.2	31.5	9.0	12.8	.6		
49	1120	Galatia, Saline Co.	7	1.20	.07	45.4	25.3	16.9	11.6	.8		
50	1121	Norris City, White Co.	7	.41	.20	41.4	34.6	10.6	12.1	1.2		
51	...	Taylorville, Scrgs. Comp.	...			45.1	21.5	19.8	12.4	1.2		
52	6121	Marion, W. Nut.	7			51.7	19.3	24.6	2.4	1.0		
53	6122	Lincoln, scrgs.	5			49.2	20.7	17.1	11.9	1.1		
54	6123	Lincoln, scrgs.	5			55.9	13.0	23.6	6.7	.8		
55	6129	La Salle, W. scrgs.	5			40.3	34.0	22.8	2.0	.9		
56	6130	Pawnee, Lump.	6			33.1	42.5	17.9	5.6	.9		
57	6131	Pawnee, Lump.	6			54.2	16.4	24.2	4.1	1.2		
58	6132	Vigo County, Indiana.	...			32.9	43.8	20.5	2.9	.9		
59	6133	Vigo County, Indiana.	...			35.1	35.6	25.3	2.3	.8		
60	6134	Sullivan Co., Indiana.	...			45.8	20.2	28.3	5.4	.0		
61	6135	Sullivan Co., Indiana.	...			27.1	52.3	14.1	4.4	1.2		
62	6290	Marion, Williamson Co., Ill.	7			54.1	12.1	23.8	6.7	1.2		

V. SUMMARY

The principles developed by the foregoing discussion may be stated as follows:

1. Ordinarily the total inorganic or non-coal constituent is expressed by the formula

$$\text{Total Inorganic Matter} = M + 1.08 A + 22/40 S$$

in which M = moisture, A = ash, and S = sulphur. The formula for calculating the heat value for unit coal, therefore, basing the calculation upon wet coal values, would be

$$\text{B. t. u. of Unit Coal} = \frac{\text{Indicated (wet) B. t. u.} - 5000 S}{1.00 - (M + 1.08 A + 22/40 S)}$$

and for dry coal:

$$\text{B. t. u. of Unit Coal} = \frac{\text{Indicated (dry) B. t. u.} - 5000 S}{1.00 - (1.08 A + 22/40 S)}$$

2. A coal of unknown character as to its carbonate content should be subjected to a carbonate determination readily effected by liberating the CO₂ with acid and measuring the same by weight or volume. Where carbonates are found to exist in any considerable quantity, say over 0.3 per cent CO₂, the ash determination should be made by blasting in a platinum crucible to constant weight, and the ash as thus determined corrected by adding the weight found for CO₂. Further, since this method of driving the weight of ash will drive off the chlorine present, this constituent should also be determined and the amount as Cl added to the weight of ash.

It has been possible to apply the foregoing principles to a large number of analyses which have been made in this laboratory. Some from the same mine extending over a considerable period of time afford a good opportunity of verifying the constancy of the unit coal values from the same mine. Others from the same geological seam, extending over a considerable area, as well as those from neighboring mines, serve to demonstrate a positive relationship and, so far as they are available, establish the unit values for their respective regions. An extension of these data has been prepared and arranged in tables following

this discussion. In addition to the results obtained in our own laboratory, the various coal values as published by the Ohio State Survey¹ (Appendix A) and the United States Geological Survey² (Appendix B) have been calculated to unit values by the formula already developed and indicated at the head of the column for "Unit Coal." A most interesting study is there made possible of the constancy of values for a given type of coal or for a given region.

The application which the facts of the tables may be made to serve are many and of far-reaching importance. The real value and the extent of this service hinge upon the accuracy with which we may differentiate between the actual or unit coal and the true ash content. It is believed that the methods and formulas herein proposed are accurate within the limits of variation, inherent in the composition of the unit substance itself, and in the manipulation and methods of analysis employed. Concerning this latter point, it is obviously impossible in applying the calculations to analytical values already published, to take account of errors in ash determination, due for example to the presence of carbonate of lime. Some of the discrepancies in unit values, therefore, may be due to this fact. Moreover, some of the samples grouped by counties may be from different seams and hence show a difference in their unit values. It has not been practicable to give more detail of location or deposit than is contained in the tables, but the facts thus presented seem to have sufficient value to warrant their publication in this form.

An inspection of Table 10, (p. 31), shows a number of coals with over 2 per cent of CO_2 present. This represents approximately 5 per cent of calcium carbonate. In the Mahler type of calorimeter, this material is decomposed, representing a loss of heat amounting to about 40 B. t. u. for each 5 per cent of calcium carbonate present. A question is therefore raised as to the desirability of correcting heat values obtained by that instrument, to take account of this reaction in the calorimeter.

¹Geological Survey of Ohio, Fourth Series, Bul. No. 9, 1908.

²United States Geological Survey, Bulletins No. 261, No. 290, and No. 332.

VI. CONCLUSIONS

1. The actual or unit coal of a given deposit or region is remarkably uniform in composition, as shown by the constancy of heat values, when calculated to such unit substance.

2. The true percentage content of the actual or unit coal hinges upon the correct determination of the inorganic constituents of the coal. The present methods of analysis fail to take account of such constituents as the hydration of the shaley or clayey portions of the ash or the carbon dioxide content of earthy carbonates. The presence of chlorine compounds may sometimes be sufficient in amount to require consideration and estimation.

3. Coal with an ash of unknown composition should be examined for carbonates and chlorides. If the combined amount of these constituents approximates 0.5 per cent, the ash determination should be made at a temperature sufficiently high for their complete elimination, and a correction made for the ash value thus obtained by adding the amount of CO_2 and Cl found.

4. Apart from the corrections which may be called for on account of the presence of CO_2 or Cl, a factor for hydration is necessary, amounting to 8 per cent of the ash as determined, minus the ferric oxide resulting from the decomposition of the iron pyrites.

5. The assembling of the corrections indicated may be embodied in a simple formula, easy of application, and under two headings as follows:

For coals free from carbonates and chlorides

$$\text{Unit B. t. u.} = \frac{\text{Indicated Dry B. t. u.} - 5000 \text{ S}}{1.00 - (1.08 \text{ Ash} + 22/40 \text{ S})}$$

For coals with carbonates and chlorides

$$\text{Unit B. t. u.} = \frac{\text{Indicated Dry B. t. u.} - 5000 \text{ S}}{1.00 - [(\text{Ash at high temp.} + \text{CO}_2 + \text{Cl}) 1.08 + 22/40 \text{ S.}]}$$

VII. TABULATION OF CALCULATED VALUES FOR UNIT COAL

From the tables following, (Tables 11 to 19 inclusive), not only is there evidence of a constancy of values for a given area, but, conversely, a given type of fuel over widely separated areas has a value which varies between relatively narrow limits and may be made to serve as an index of the kind or type and probably the region from which the material comes. From an inspection of these and other data a tentative series of values defining the suggested limits for the generally recognized fuel types is given in Table 11.

TABLE 11

CLASSIFICATION OF FUEL TYPES BY HEAT VALUES FOR UNIT OR ACTUAL ORGANIC SUBSTANCE

Cellulose and wood.....	6500 to 7800
Peat.....	7800 to 11500
Lignite-brown.....	11500 to 12500
Lignite-black.....	12500 to 13500
Sub-bituminous Coal.....	13500 to 14200
Bituminous Coal (mid continental field).....	14200 to 15000
Bituminous Coal (eastern field).....	15000 to 16000
Semi-anthracite and Semi-bituminous.....	15500 to 16000
Anthracite.....	15000 to 15500

TABLE 12
COAL RESULTS

From Continuous Deliveries, September 1, 1907 to September 1, 1908.
Each Sample Represents 5 Cars or 250 Tons, and is a Composite of 5 Separate Samples.

Shipments all from the Same Mine, Christian Co., Ill.

Lab. No.	ANALYSES OF SAMPLES AS RECEIVED				"Unit Coal" Basis	Variation from Av- erage B. t. u.
	Moisture	Ash	Sulphur	B. t. u.	B. t. u. — 5000 S 1.00 — (1.08 Ash + $\frac{22}{40}$ S.)	
923	13.16	17.07	4.39	9665	14313	— 160
934	10.89	17.34	4.87	10104	14564	+ 91
935	13.49	15.14	3.99	10082	14539	+ 66
936	13.76	16.26	4.01	9845	14507	+ 34
937	14.00	16.97	4.41	9680	14499	+ 26
938	12.55	17.40	4.19	9883	14576	+ 103
939	12.57	18.70	4.43	9709	14643	+ 170
940	12.99	16.25	4.10	9971	14533	+ 60
941	12.71	17.27	4.55	9871	14580	+ 107
942	12.18	18.53	5.35	9724	14577	+ 104
943	11.52	16.13	4.36	10211	14554	+ 81
944	12.21	15.31	4.32	10278	14608	+ 135
945	13.53	16.14	4.38	9824	14420	— 53
946	14.99	14.96	4.15	9885	14537	+ 64
947	15.07	15.09	4.27	9825	14501	+ 28
948	14.25	15.51	3.91	9896	14510	+ 37
949	12.98	15.25	3.70	10076	14437	— 36
957	13.17	16.40	4.16	9880	14472	— 1
990	13.03	18.05	4.39	9773	14683	+ 210
1024	14.59	16.20	4.18	9830	14664	+ 191
1025	13.38	17.51	4.19	9747	14580	+ 107
1026	14.28	16.31	4.71	9840	14558	+ 185
1027	13.84	16.56	4.23	9842	14602	+ 129
1071	13.88	16.06	4.51	9868	14543	+ 70
1072	13.66	16.31	4.46	9837	14505	+ 32
1073	12.99	15.71	4.15	10076	14563	+ 90
1074	12.43	17.95	4.66	9834	14631	+ 158
1075	12.70	17.01	4.12	9857	14478	— 5
1076	13.79	18.63	4.95	9497	14595	+ 122
1077	13.62	15.90	4.36	9935	14544	+ 71
1180	13.45	16.68	4.00	9801	14472	— 1
1181	13.17	17.95	4.85	9607	14457	— 16
1182	13.49	13.36	3.97	9964	14415	— 58
1183	12.16	19.20	5.01	9556	14462	— 11
1184	11.90	17.16	4.55	9925	14458	— 15
1185	12.97	16.63	4.60	9893	14522	+ 49
1186	13.73	16.66	4.34	9795	14536	+ 63
1187	13.80	16.10	4.27	9884	14550	+ 77
1188	14.28	15.84	4.54	9763	14424	— 49
1204	14.51	18.04	4.35	9464	14533	+ 60

TABLE 12
COAL RESULTS—(Concluded)

Lab. No.	ANALYSES OF SAMPLES AS RECEIVED				"Unit Coal" Basis	Variation from Av- erage B. t. u.
	Moisture	Ash	Sulphur	B. t. u.	B. t. u. — 5000 S 1.00 — (1.08 Ash + $\frac{22}{40}$ S.)	
1205	14.13	16.31	4.85	9746	14488	+ 15
1272	15.81	15.18	3.86	9650	14399	— 74
1273	15.21	14.45	4.04	9910	14498	+ 25
1274	15.40	16.08	5.03	9560	14440	— 33
1275	14.04	16.44	4.52	9694	14409	— 64
1276	14.35	18.13	4.62	9315	14299	—174
1326	14.81	16.56	4.22	9540	14354	—119
1327	13.46	17.87	4.65	9505	14335	—138
1328	13.56	17.53	4.67	9568	14373	—100
1329	14.98	14.37	3.90	9928	14451	— 22
1330	14.59	16.63	4.34	9614	14444	— 29
1331	14.10	17.42	4.82	9592	14511	+ 38
1332	13.13	16.12	4.58	9783	14272	—201
1447	13.28	17.10	4.19	9670	14346	—127
1448	12.62	18.18	4.46	9590	14344	—129
1449	13.31	18.15	4.50	9584	14485	+ 12
1450	13.21	16.16	4.21	9852	14385	— 88
1451	13.32	17.01	4.28	9656	14313	—160
1695	15.31	13.19	3.61	9999	14341	—132
1696	16.12	13.10	3.76	9890	14339	—134
1697	15.62	14.29	3.61	9782	14338	—135
1759	14.02	15.62	4.43	9817	14392	— 81
1760	13.83	16.54	4.49	9676	14354	—119
1789	13.49	19.41	4.07	9331	14416	— 57
1832	14.09	17.22	4.17	9605	14451	— 22
1833	13.56	17.07	3.93	9704	14439	— 34
1834	13.56	17.50	4.24	9590	14381	— 92
Av....	13.65	16.58	4.35	9779	14475	± 82

TABLE 13
COAL RESULTS

From Continuous Deliveries September 1, 1908, to May 1, 1909

Each Sample represents 300 Tons

Shipments all from the Same Mine, Vermilion Co., Ill.

Lab. No.	ANALYSES OF SAMPLES AS RECEIVED				"Unit Coal" Basis	Variation from Av- erage B. t. u.
	Moisture	Ash	Sulphur	B. t. u.	B. t. u. — 5000 S 1.00 — (1.08 Ash + $\frac{22}{40}$ S.)	
1879	12.92	16.58	3.82	9992	14613	-143
1880	14.22	18.16	4.51	9540	14624	-132
1881	12.45	17.22	4.14	9950	14608	-148
1883	13.00	19.48	4.31	9501	14601	-155
1896	12.08	17.13	3.67	10160	14801	+ 45
1897	12.67	16.90	4.26	10062	14757	+ 1
1898	12.71	16.79	4.22	10071	14752	- 4
1899	12.36	18.80	5.17	9801	14794	+ 38
1900	12.36	16.53	5.07	10170	14800	+ 44
1902	12.70	15.20	3.89	10269	14655	-101
1903	12.65	15.27	3.78	10208	14567	-189
1905	12.38	18.00	4.59	9913	14747	- 9
1906	12.46	18.30	4.21	9787	14629	-127
1908	11.76	16.12	3.48	10402	14840	+ 84
1909	11.74	15.10	3.93	10440	14677	- 79
1911	12.34	16.19	4.23	10324	14903	+147
1912	12.59	18.25	4.10	9772	14620	-136
1919	16.76	16.68	3.70	9512	14760	+ 4
1920	16.92	18.20	3.83	9232	14745	- 11
1934	12.93	16.44	3.54	10200	14878	+122
1942	12.72	17.62	4.07	9949	14763	+ 7
1943	15.03	16.45	4.09	9846	14844	+ 88
1947	13.90	18.31	4.08	9689	14800	+ 44
1990	14.47	15.57	3.85	10021	14759	+ 3
1991	13.31	18.08	4.35	10020	15134	+378*
1987	12.80	14.51	3.64	10476	14805	+ 49
1988	12.68	14.54	3.80	10508	14840	+ 84
1993	13.19	17.33	4.16	9931	14777	+ 21
1994	13.31	18.44	4.15	9849	14947	+191
1996	11.85	20.36	5.47	9720	14958	+202
1997	12.05	20.83	4.13	9512	14728	- 28
2007	13.73	19.23	3.91	9527	14729	- 27
2008	13.53	18.60	4.33	9638	14720	- 36
2016	13.38	19.72	4.42	9583	14886	+130
2017	13.28	18.24	4.56	9797	14833	+ 77
2013	12.48	21.14	5.11	9348	14693	- 63
2014	12.89	18.78	3.78	9742	14880	+124
2029	14.24	19.64	4.47	9431	14829	+ 73
2030	15.90	16.35	3.75	9667	14724	- 32
2031	14.11	17.36	3.97	9677	14591	-165
2032	13.66	15.43	3.77	10173	14767	+ 11

* Probably due to error in ash determination.

TABLE 13
COAL RESULTS—(Concluded)

Lab. No.	ANALYSES OF SAMPLES AS RECEIVED				"Unit Coal" Basis	Variation from Av- erage B. t. u.
	Moisture	Ash	Sulphur	B. t. u.	B. t. u. — 5000 S	
					1.00 — (1.08 Ash + $\frac{22}{40}$ S.)	
2057	13.61	15.71	4.13	10128	14775	+ 19
2071	12.16	18.31	3.98	9986	14856	+ 100
2072	12.22	18.93	3.93	9857	14821	+ 65
2073	13.10	20.38	3.99	9520	14864	+ 108
2074	12.47	19.37	4.04	9791	14892	+ 136
2106	13.31	17.49	4.03	9816	14660	— 96
2107	14.07	17.50	4.43	9742	14739	— 17
2108	13.12	17.25	4.41	9987	14837	+ 81
2145	12.81	16.82	3.98	10066	14764	+ 8
2146	13.97	15.64	4.76	9813	14632	— 124
2147	13.19	17.68	4.21	9805	14668	— 68
2159	13.30	17.98	4.17	9831	14805	+ 49
2160	12.20	20.14	4.78	9628	14805	+ 49
2161	13.12	17.61	4.34	9900	14790	+ 34
2178	14.83	19.77	3.90	9319	14793	+ 37
2179	14.01	17.92	4.13	9858	14993	+ 237*
2180	13.03	19.92	4.11	9503	14710	— 46
2232	14.07	17.40	4.12	9815	14813	+ 57
2233	13.26	19.54	4.25	9381	14483	— 273*
2234	12.26	18.90	3.95	9611	14446	— 310*
2235	13.02	17.94	4.46	9706	14547	— 209
2304	15.07	19.03	4.42	9346	14730	— 26
2305	14.22	16.93	4.81	9718	14614	— 142
2324	15.16	16.98	3.72	9706	14771	+ 15
2325	15.33	16.60	3.77	9792	14849	+ 93
2326	11.99	19.10	4.13	9801	14735	— 21
2369	12.00	18.42	3.92	9900	14712	— 44
2370	14.29	18.74	4.63	9498	14727	— 29
2371	13.28	17.33	4.17	9897	14744	— 12
2416	13.55	18.55	4.48	9630	14706	— 50
Av....	13.30	17.79	4.18	9828	14756	± 86

* Probably due to error in ash determination.

TABLE 14

COAL RESULTS

Run-of-Mine Coal from Two Mines, Boulder Co., Colo.

No.	ANALYSES OF SAMPLES AS RECEIVED				"Unit Coal" Basis	Variation from Av- erage B. t. u.
	Moisture	Ash	Sul.	B. t. u.	B. t. u. — 5000S 1.00— (1.08 Ash + $\frac{22}{40}$ S.)	
13	19.59	8.38	.52	9349	13118	+120
15	20.18	8.15	.39	9362	13193	+195
19	20.26	6.85	.38	9434	13053	+ 55
20	19.64	6.83	.36	9519	13054	+ 56
22	19.49	7.23	.48	9580	13192	+194
24	19.43	5.77	.38	9625	12958	— 40
25	19.12	7.16	.42	9620	13164	+166
27	20.43	6.40	.36	9512	13102	+104
30	19.65	8.55	.41	9271	13048	+ 50
31	19.91	6.75	.38	9425	12958	— 40
35	20.32	7.85	.44	9431	13260	+262
37	19.71	4.88	.38	9779	13046	+ 48
5	20.23	5.81	.35	9373	12761	—237
7	19.73	5.08	.29	9598	12842	—156
8	19.64	5.97	.30	9497	12859	—139
9	19.83	5.54	.29	9573	12911	— 87
13	20.06	5.51	.33	9551	12917	— 81
18	20.08	4.82	.38	9632	12902	— 96
19	19.96	5.63	.30	9588	12972	— 26
34	19.99	6.55	.40	9441	12955	— 43
38	19.38	5.11	.27	9712	12939	— 59
42	19.96	6.95	.25	9422	12998	00
45	20.56	5.60	.26	9428	12853	—145
76	18.09	5.56	.41	9835	12907	— 91
Av.....	19.80	6.37	.36	9523	12998	±104

TABLE 15
COAL RESULTS
Run-of-Mine Coal from One Mine, Las Animas Co., Colo.

No.	ANALYSES OF SAMPLES AS RECEIVED				"Unit Coal" Basis B. t. u. — 5000S	Variation from Av- erage B. t. u.
	Moisture	Ash	Sul.	B. t. u.	1.00 — (1.08 Ash + $\frac{22}{40}$ S.)	
2	2.25	9.72	.89	13309	15288	— 4
10	2.40	11.33	.68	13066	15334	+ 42
12	2.51	14.49	.68	12547	15359	+ 67
14	2.63	11.32	.61	13033	15332	+ 40
15	2.93	11.53	.61	13065	15465	+173
16	2.57	12.81	.60	12842	15386	+ 92
21	2.80	20.17	.65	11643	15468	+176
23	2.26	9.45	.60	13297	15214	— 78
25	2.43	14.86	.60	12572	15448	+156
33	2.02	11.14	.63	13025	15144	—148
37	2.95	13.01	.59	12532	15121	—171
41	3.65	12.22	.63	12584	15159	—133
44	2.48	12.77	.58	12722	15218	— 74
46	2.19	11.57	.61	12904	15150	—142
Av.....	2.58	12.59	.64	12796	15292	±107

TABLE 16
ILLINOIS "No. 2" COAL

Lab. No.	LOCALITY	Total Mois- ture	REFERRED TO DRY COAL			"Unit Coal" Basis B. t. u. — 5000 S 1.00 — (1.08 Ash + $\frac{22}{40}$ S.)
			Ash	Sul.	B. t. u.	
1764	Bureau Co.....	15.61	9.59	4.29	13008	14657
1769	Bureau Co.....	15.99	8.96	4.04	13191	14743
1860	Brown Co.....	15.60	10.02	6.01	13099	14904
1869	Christian Co.....	11.54	10.08	4.38	13148	14912
1811	Fulton Co.....	15.37	7.55	3.67	13558	14888
1839	Green Co.....	14.93	12.43	5.79	12581	14739
1840	Green Co.....	15.04	12.38	6.03	12538	14687
733	Grundy Co.....	14.69	8.17	3.62	13217	14616
1787	Grundy Co.....	17.18	6.82	3.11	13450	14622
734	Grundy Co.....	14.16	5.82	1.83	13436	14395
1861	Hancock Co.....	13.48	6.88	4.29	13516	14744
1875	Jackson Co.....	14.25	4.99	.79	14113	14943
1878	Jackson Co.....	12.73	4.75	.71	14115	14902
1876	Jackson Co.....	9.00	6.87	2.02	13799	14975
1765	La Salle Co.....	14.03	9.77	3.36	13033	14686
1785	La Salle Co.....	12.41	8.89	3.23	13329	14858
1768	LaSalle Co.....	15.36	14.03	5.34	12241	14618
1775	Marshall Co.....	14.60	7.29	1.90	13539	14761
1795	Marshall Co.....	13.54	6.66	2.90	13743	14908
1831	McDonough Co.....	16.42	8.18	3.23	13418	14829
1748	Mc Lean Co.....	12.02	10.13	3.36	12980	14704
1857	Mercer Co.....	17.56	11.58	5.47	12666	14669
1411	Peoria Co.....	12.05	10.90	4.48	12866	14739
1802	Warren Co.....	18.52	5.45	3.20	13650	14606
1793	Woodford Co.....	16.18	8.33	3.55	13361	14802

TABLE 17

ILLINOIS "No. 5" COAL FROM SOUTHERN PART OF STATE

Lab. No.	LOCALITY	Total Mois- ture	REFERRED TO DRY COAL			"Unit Coal" Basis
			Ash	Sul.	B. t. u.	B. t. u. — 5000 S 1.00 — (1.08 Ash + $\frac{22}{40}$ S.)
1092	Gallatin Co.....	4.47	10.85	3.72	13235	15133
1094	Saline Co.....	6.03	10.54	3.12	13212	15024
1095	Saline Co.....	4.89	11.49	4.16	12931	14916
1110	Saline Co.....	4.34	12.68	6.12	12879	15157
1111	Saline Co.....	6.64	9.21	2.35	13367	14927
1112	Saline Co.....	6.10	8.99	3.52	13415	15019
1113	Saline Co.....	5.97	7.62	2.30	13700	15011
1114	Saline Co.....	4.43	9.04	2.47	13450	14993
1115	Saline Co.....	6.04	11.58	3.26	12942	14911
1116	Saline Co.....	6.13	9.89	2.37	13298	14973
896	Williamson Co.....	6.29	10.68	3.86	13073	14930
1809	Williamson Co.....	6.47	12.53	3.62	12853	15000

TABLE 18

ILLINOIS "No. 5" COAL FROM CENTRAL PART OF STATE

Lab. No.	LOCALITY	Total Mois- ture	REFERRED TO DRY COAL			"Unit Coal" Basis
			Ash	Sul.	B. t. u.	B. t. u. — 5000 S 1.00 — (1.08 Ash + $\frac{22}{40}$ S.)
1404	Fulton Co.....	15.09	12.52	3.79	12450	14527
1807	Fulton Co.....	15.03	12.98	2.95	12389	14510
1808	Fulton Co.....	15.49	13.43	3.81	12364	14594
1856	Fulton Co.....	15.44	12.22	4.17	12666	14740
1771	La Salle Co.....	13.13	12.19	4.15	12544	14590
1788	Livingston Co.....	12.73	12.15	3.67	12853	14929
1569 ^a	Macon Co.....	13.91	11.33	3.82	12549	14427
1874	Macon Co.....	14.07	11.82	4.28	12545	14529
1749	Mc Lean Co.....	12.56	14.06	4.74	12299	14672
1847	Mc Lean Co.....	14.15	13.54	2.82	12485	14725
1848	Menard Co.....	15.55	12.20	3.58	12590	14627
1403	Peoria Co.....	14.29	15.46	3.16	12094	14635
1407	Peoria Co.....	13.86	16.25	3.91	12044	14755
1408	Peoria Co.....	13.91	15.23	3.39	12189	14713
1409	Peoria Co.....	13.45	16.66	3.58	12014	14786
1410	Peoria Co.....	14.73	14.78	3.97	12257	14730
540	Sangamon Co.....	13.56	10.76	4.78	12749	14589
721	Sangamon Co.....	14.39	13.64	4.61	12304	14593
740	Sangamon Co.....	14.30	12.75	4.11	12369	14468
741	Sangamon Co.....	13.13	12.47	4.28	12416	14495
1794	Sangamon Co.....	13.69	14.26	3.88	12133	14477
1761	Sangamon Co.....	14.61	12.48	4.55	12364	14444
1762	Sangamon Co.....	14.56	12.85	4.54	12281	14415
1766	Sangamon Co.....	15.42	14.73	4.19	12082	14515
1767	Sangamon Co.....	15.53	12.68	3.83	12340	14427
1770	Sangamon Co.....	14.89	11.32	4.79	12663	14591
1772	Sangamon Co.....	14.00	12.83	4.06	12358	14486
1773	Sangamon Co.....	14.44	11.71	4.85	12477	14447
1774	Sangamon Co.....	14.41	11.80	5.09	12550	14557
1786	Sangamon Co.....	14.18	14.67	5.00	12115	14574
1790	Sangamon Co.....	16.41	10.69	3.65	12685	14477
1791	Sangamon Co.....	15.44	12.91	4.01	12301	14430
1792	Sangamon Co.....	15.38	10.14	4.00	12849	14578
1812	Schuyler Co.....	12.99	12.76	4.31	12709	14899
1868	Shelby Co.....	11.26	13.63	4.93	12373	14686
1412	Tazewell Co.....	14.30	11.49	3.90	12690	14623
1413	Tazewell Co.....	14.35	12.45	3.53	12504	14569
720	Logan Co.....	14.80	13.81	3.56	12426	14733
1889	Logan Co.....	11.83	12.25	3.83	12376	14392

TABLE 19
BLUE BAND COAL

Lab. No.	LOCALITY	Total Mois- ture	REFERRED TO DRY COAL			"Unit Coal" Basis B. t. u. — 5000 S 1.00— (1.08 Ash + ²² / ₄₀ S.)
			Ash	Sul.	B. t. u.	
742	Christian Co.....	11.82	13.50	4.71	12203	14448
1870	Christian Co.....	15.15	9.97	3.70	12745	14405
1871	Christian Co.....	14.88	10.67	4.04	12696	14484
996	Clinton Co.....	10.97	10.47	4.80	12815	14614
997	Clinton Co.....	13.05	13.98	5.29	12232	14596
1177	Clinton Co.....	15.19	11.15	1.65	12569	14342
1178	Clinton Co.....	14.81	16.56	2.99	11639	14262
1175	Clinton Co.....	11.83	10.78	3.96	12659	14459
1176	Clinton Co.....	12.86	13.59	4.52	12246	14512
1845	Edgar Co.....	14.94	11.00	3.02	12890	14734
1846	Edgar Co.....	14.82	11.42	3.34	12797	14715
461	Franklin Co.....	14.40	8.08	1.19	13400	14722
419	Franklin Co.....	11.19	10.11	.60	12985	14597
420	Franklin Co.....	10.06	7.53	.91	13312	14519
1810	Franklin Co.....	10.13	10.29	.78	12945	14590
1722	Franklin Co.....	8.47	10.55	2.13	12778	14491
1723	Franklin Co.....	9.09	8.78	1.21	13173	14595
1776	Franklin Co.....	9.11	6.42	1.33	13620	14679
1777	Franklin Co.....	8.48	7.32	1.33	13527	14734
1799	Jackson Co.....	7.81	13.20	3.85	12650	14897
1800	Jackson Co.....	9.14	10.22	.68	12970	14603
1651	Jefferson Co.....	7.48	11.35	3.34	12824	14735
1652	Jefferson Co.....	7.85	12.10	4.19	12611	14655
735	Macoupin Co.....	12.80	10.86	5.38	12469	14301
736	Macoupin Co.....	12.71	11.40	4.41	12360	14238
737	Macoupin Co.....	12.17	12.87	5.48	12303	14477
738	Macoupin Co.....	12.80	11.90	4.33	12440	14419
1841	Macoupin Co.....	12.89	12.68	6.49	12214	14369
1862	Macoupin Co.....	13.93	12.29	5.23	12371	14441
725	Madison Co.....	11.68	11.22	4.85	12762	14692
1117	Madison Co.....	10.33	10.59	4.12	12681	14457
1118	Madison Co.....	14.16	13.65	2.81	12114	14303
1119	Madison Co.....	11.20	11.72	5.17	12499	14485
1866	Marion Co.....	10.31	14.96	5.61	12167	14720
1842	Montgomery Co.....	13.61	8.50	4.37	13473	14990
1864	Montgomery Co.....	12.84	10.58	4.30	12743	14534
1863	Montgomery Co.....	14.76	9.98	4.60	12712	14398
1873	Montgomery Co.....	13.21	11.51	4.90	12570	14522
421	Perry Co.....	9.31	14.71	.98	12181	14517
1523	Perry Co.....	11.03	12.63	1.01	12453	14456
1614	Perry Co.....	10.37	13.92	3.93	12293	14607
1615	Perry Co.....	9.87	13.86	3.28	12261	14534
1591	Perry Co.....	11.11	15.89	4.34	11859	14471
1592	Perry Co.....	10.49	12.17	3.84	12361	14359
1835	Perry Co.....	10.55	12.12	4.50	12393	14412
1610	Randolph Co.....	10.72	14.55	5.07	11978	14385

TABLE 19
BLUE BAND COAL—(Concluded)

Lab. No.	LOCALITY	Total Moisture	REFERRED TO DRY COAL			"Unit Coal" Basis
			Ash	Sul.	B. t. u.	B. t. u. — 5000 S 1.00 — (1.08 Ash + $\frac{22}{40}$ S.)
1616	Randolph Co.....	9.93	13.41	5.36	12245	14505
1120	Saline Co.....	5.98	13.79	3.73	12505	14830
722	Sangamon Co.....	14.96	11.04	4.55	12640	14503
1763	Sangamon Co.....	14.69	10.98	4.95	12503	14349
739	Sangamon Co.....	13.14	12.23	5.03	12372	14425
723	St. Clair Co.....	12.11	12.23	4.37	12604	14676
724	St. Clair Co.....	12.23	9.69	3.33	12982	14612
991	St. Clair Co.....	9.76	15.80	4.76	12202	14895
995	St. Clair Co.....	10.05	12.47	4.19	12587	14694
993	St. Clair Co.....	9.44	11.23	4.37	12723	14630
1001	St. Clair Co.....	13.75	12.53	2.13	12486	14512
1002	St. Clair Co.....	13.15	13.43	3.23	12290	14486
1003	St. Clair Co.....	9.41	12.94	4.90	12701	14948
1129	St. Clair Co.....	15.91	11.07	4.70	12706	14593
1130	St. Clair Co.....	11.11	12.00	4.72	12587	14625
1174	St. Clair Co.....	15.46	12.73	4.02	12428	14549
1600	St. Clair Co.....	11.43	15.14	5.69	11908	14435
557	Vermilion Co.....	12.56	9.15	1.41	13058	14537
558	Vermilion Co.....	12.96	8.03	1.78	13304	14626
1540	Vermilion Co.....	17.73	11.95	1.15	12561	14463
1843	Vermilion Co.....	13.23	11.43	3.17	12842	14761
1844	Vermilion Co.....	13.41	9.76	3.52	13083	14748
1643	Washington Co.....	10.41	11.34	4.35	12468	14351
1121	White Co.....	6.71	11.50	4.46	12744	14708
459	Williamson Co.....	9.99	8.48	1.03	13323	14701
460	Williamson Co.....	9.50	10.13	1.12	13078	14724
1088	Williamson Co.....	6.69	10.65	2.50	13016	14795
462	Williamson Co.....	9.39	7.66	1.89	13475	14754
1611	Williamson Co.....	10.15	9.73	1.06	13229	14763
1612	Williamson Co.....	6.12	13.76	4.42	12461	14799
1567	Williamson Co.....	6.80	11.84	2.96	12788	14770
1613	Williamson Co.....	9.69	10.23	1.16	13077	14742
1801	Williamson Co.....	9.75	8.13	1.71	13438	14791
1805	Williamson Co.....	7.58	12.10	3.85	12698	14745
1806	Williamson Co.....	9.79	9.85	2.19	13048	14676
1804	Williamson Co.....	6.77	13.29	5.08	12517	14800
1917	Williamson Co.....	8.86	9.65	1.15	13103	14685
1918	Williamson Co.....	9.34	9.50	1.74	13172	14739

APPENDIX A

TABLE 20
UNIT COAL VALUES

Compiled from Bulletin 9, Fourth Series, 1908, Ohio State Geological Survey

No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis
		Mois- ture	Ash	Sul- phur	B. t. u.	B. t. u. — 5000 S 1.00 — (1.08 Ash + $\frac{22}{40}$ S.)

CLARION OR NO. 4 COAL

65	Lawrence.....	6.34	17.41	5.29	10741	14562
67	Lawrence.....	5.86	15.28	5.36	11133	14547
68	Lawrence.....	6.11	9.94	3.61	11957	14508
66	Lawrence.....	6.00	11.86	5.10	11734	14645
64	Scioto.....	6.80	9.34	3.45	11763	14272
63	Jackson.....	4.90	13.70	6.14	11495	14545
62	Jackson.....	5.31	13.54	6.08	11381	14436
55	Jackson.....	5.61	8.09	3.70	12279	14465
56	Jackson.....	4.98	9.80	4.08	12154	14538
57	Jackson.....	4.71	8.61	3.73	12361	14505
60	Jackson.....	5.33	8.40	3.72	12206	14387
59	Vinton.....	4.72	11.21	4.16	12049	14640
61	Vinton.....	4.52	8.85	4.23	12337	14505
54	Vinton.....	5.02	8.15	2.81	12469	14639
58	Vinton.....	4.61	11.10	5.28	12053	14645
70	Vinton.....	5.02	8.97	3.32	12528	14780
69	Vinton.....	4.95	9.32	3.53	12445	14775
	Average.....	5.34	10.80	4.33	11947	14551

LOWER KITTANING OR NO. 5 COAL

74	Lawrence.....	7.57	8.79	3.20	12199	14830
75	Lawrence.....	8.07	9.71	2.13	11927	14727
76	Jackson.....	8.39	7.42	2.65	12190	14679
71	Perry.....	6.85	10.16	4.72	11864	14612
72	Perry.....	6.74	7.12	2.58	12393	14574
73	Muskingum.....	5.05	7.77	4.80	12569	14691
77b	Jefferson.....	2.46	7.40	3.82	13664	15406
77	Tuscarawas.....	5.30	7.71	3.25	12902	15061
77a	Mahoning.....	5.23	4.72	2.17	13504	15141
	Av.....	6.18	7.87	3.26	12578	14863

MIDDLE KITTANING OR NO. 6 COAL

136	Lawrence.....	5.99	4.82	3.61	13165	14957
82a	Lawrence.....	6.64	10.92	3.32	11927	14749
82b	Gallia.....	8.08	8.52	3.64	12091	14753
89a	Athens.....	6.36	8.49	0.51	12454	14764
83	Athens.....	6.17	7.82	0.90	12362	14511
84	Athens.....	6.70	6.75	2.28	12458	14563

TABLE 20
UNIT COAL VALUES—(Continued)

No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis B. t. u. — 5000 S 1.00 — (1.08 Ash + ²² / ₄₀ S.)
		Mois- ture	Ash	Sul- phur	B. t. u.	
85	Athens.....	6.80	8.05	2.14	12229	14547
82	Vinton.....	4.90	10.15	4.25	12321	14802
81	Hocking.....	6.52	8.03	3.52	12330	14666
89	Athens.....	7.14	6.72	1.65	12353	14488
90	Athens.....	7.28	6.73	0.86	12409	14552
86	Hocking.....	7.55	5.85	0.77	12510	14552
87	Hocking.....	7.45	4.81	0.66	12703	14563
88	Hocking.....	7.40	5.00	1.06	12649	14542
80	Hocking.....	6.55	6.97	2.57	12422	14548
79	Perry.....	7.76	7.47	1.45	12190	14534
91	Perry.....	5.79	5.91	1.00	12569	14510
78	Perry.....	7.00	6.95	2.33	12384	14569
92	Perry.....	5.25	9.86	3.43	12191	14620
93	Perry.....	5.90	10.10	4.96	12035	14649
95	Perry.....	6.72	6.64	2.43	12425	14513
94	Perry.....	7.21	5.26	2.34	12614	14562
97	Perry.....	5.70	8.45	3.38	12332	14600
98	Perry.....	6.40	7.58	2.72	12361	14569
101	Muskingum.....	5.08	9.77	5.54	12244	14716
100	Muskingum.....	4.67	9.83	4.10	12371	14756
96	Muskingum.....	5.02	9.56	5.97	12164	14581
99	Muskingum.....	5.44	9.28	3.77	12280	14663
104	Muskingum.....	5.55	5.23	3.63	12944	14703
102	Muskingum.....	4.75	9.28	5.35	12337	14668
103	Muskingum.....	4.62	6.58	4.49	12827	14689
111	Coshocton.....	4.37	5.36	3.61	13045	14643
112	Coshocton.....	10.93	6.64	2.03	11039	13871*
108	Coshocton.....	4.33	5.59	4.00	13084	14736
109	Coshocton.....	5.12	7.02	3.87	12719	14708
105	Coshocton.....	5.32	6.30	4.22	12755	14661
110	Coshocton.....	5.60	13.28	4.87	11200	14159
113	Coshocton.....	4.44	4.45	3.54	13232	14702
114	Coshocton.....	4.58	8.75	5.36	12380	14589
118	Coshocton.....	5.32	8.60	4.36	12290	14546
120	Coshocton.....	4.50	5.97	3.63	12911	14623
107	Coshocton.....	5.40	5.08	3.18	12949	14641
133	Tuscarawas.....	3.45	7.67	5.22	12843	14733
131	Tuscarawas.....	3.41	9.38	4.88	12548	14686
115	Tuscarawas.....	4.72	5.47	4.05	12958	14637
130	Tuscarawas.....	3.78	8.42	3.83	12782	14808
129	Tuscarawas.....	3.81	6.01	3.24	13151	14774
124	Tuscarawas.....	4.10	5.21	3.25	13196	14730
134	Tuscarawas.....	3.18	6.93	4.12	13149	14865
116	Tuscarawas.....	5.19	5.87	3.55	12820	14613
128	Tuscarawas.....	4.30	7.63	3.97	12602	14546

* Low B. t. u. due to weathering.

TABLE 20

UNIT COAL VALUES—(Continued)

No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis
		Mois- ture	Ash	Sul- phur	B. t. u.	
						B. t. u. — 5000 S 1.00 — (1.08 Ash + $\frac{22}{40}$ S.)
117	Coshocton.....	4.70	11.29	5.60	11869	14481
106	Coshocton.....	5.30	6.15	3.72	12751	14609
121	Tuscarawas.....	3.52	6.01	3.17	13135	14705
122	Tuscarawas.....	4.94	9.50	4.19	12341	14706
123	Tuscarawas.....	3.51	7.69	4.56	12875	14761
132	Carroll.....	3.76	6.79	3.06	13028	14760
138	Tuscarawas.....	7.15	4.56	2.62	12949	14820
127	Tuscarawas.....	4.66	6.22	3.28	12775	14525
119	Holmes.....	7.31	4.21	1.00	12514	14230
125	Tuscarawas.....	4.69	9.06	4.70	12386	14649
126	Tuscarawas.....	4.92	7.04	2.91	12748	14676
135	Stark.....	6.66	8.22	2.66	12559	14971
137	Columbiana.....	3.60	4.60	1.76	14020	15401
139	Stark.....	5.65	10.08	4.13	12362	14973
	Av.....	5.56	7.36	3.30	12564	14644

UPPER FREEPORT, WATERLOO OR No. 7 COAL

147	Lawrence.....	7.20	10.67	2.33	11801	14824
144	Lawrence.....	7.85	12.18	2.66	11349	14465
145	Lawrence.....	8.37	8.23	1.29	11873	14396
146	Lawrence.....	8.45	11.28	0.93	11529	14547
142	Gallia.....	7.62	12.39	1.81	11468	14586
140	Lawrence.....	7.13	8.91	1.31	12089	14570
141	Lawrence.....	8.77	8.71	0.76	11855	14517
143	Lawrence.....	8.38	10.09	1.84	11695	14556
	Av.....	7.97	10.31	1.62	11707	14531

UPPER FREEPORT OR No. 7 COAL

148	Muskingum.....	4.89	7.78	4.36	12499	14566
149	Muskingum.....	4.72	7.56	5.00	12683	14736
150	Muskingum.....	5.11	12.60	3.84	11804	14667
151	Coshocton.....	6.40	3.19	2.01	13185	14694
	Av.....	5.28	7.78	3.80	12542	14665

TABLE 20

UNIT COAL VALUES—(Continued)

No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis
		Mois- ture	Ash	Sul- phur	B. t. u.	B. t. u. — 5000 S 1.00 — (1.08 Ash + ²² / ₄₀ S.)
PITTSBURG OR No. 8 COAL						
25	Gallia.....	5.80	10.06	4.34	11792	14301
27	Gallia.....	6.98	9.03	5.21	11849	14413
28	Gallia.....	7.83	9.76	3.89	11779	14575
26	Gallia.....	6.73	13.03	4.37	11441	14614
23	Athens.....	5.78	8.00	4.19	12299	14618
24	Athens.....	6.60	10.20	3.41	11892	14560
24	Athens.....	4.51	11.49	4.88	11945	14553
22	Morgan.....	6.87	8.19	4.22	12100	14504
9	Belmont.....	2.79	9.42	5.09	12987	14134
11	Belmont.....	4.08	10.61	4.95	12476	14961
8	Belmont.....	2.91	8.00	4.31	13212	15099
3	Belmont.....	3.51	6.86	3.76	13185	14937
4	Belmont.....	3.80	8.95	4.27	12785	14933
7	Belmont.....	3.21	7.26	4.28	13135	14920
10	Belmont.....	4.47	11.01	4.67	12375	14976
6	Belmont.....	3.75	10.84	4.76	12357	14794
5	Belmont.....	4.46	10.76	4.45	12425	14977
1	Belmont.....	3.39	7.86	2.97	12991	14850
2	Belmont.....	3.79	9.00	4.16	12861	15027
6a	Belmont.....	4.25	10.35	3.95	12425	14840
2a	Belmont.....	4.23	9.21	4.17	12605	14842
12	Jefferson.....	3.10	9.52	3.83	12875	15008
15	Jefferson.....	3.13	8.22	4.02	13019	14943
15a	Jefferson.....	4.57	9.00	1.55	12789	14980
18	Harrison.....	6.54	6.74	2.19	12710	14829
21	Harrison.....	5.98	5.97	1.35	12964	14853
20	Harrison.....	3.83	10.88	4.38	12355	14798
16	Jefferson.....	4.89	10.46	4.09	12515	15095
13	Jefferson.....	4.96	6.45	1.75	13099	14938
19	Jefferson.....	4.18	8.22	2.83	12888	14928
14	Jefferson.....	4.30	7.88	3.01	12859	14858
17	Jefferson.....	5.05	7.95	2.61	12865	14995
	Av.....	4.70	9.10	3.81	12559	14835
POMEROY OR No. 8a COAL						
34	Gallia.....	8.21	11.46	2.18	11497	14561
33	Meigs.....	4.85	12.52	2.94	11923	14718
29	Meigs.....	7.33	8.69	2.05	12105	14608
30	Meigs.....	7.22	9.29	1.32	12002	14552
31	Meigs.....	5.51	10.58	4.17	11990	14588
32	Meigs.....	7.63	10.93	1.83	11722	14618
	Av.....	6.79	10.58	2.42	11873	14608

TABLE 20
UNIT COAL VALUES—(Concluded)

No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis
		Mois- ture	Ash	Sul- phur	B. t. u.	B. t. u. — 5000 S 1.00 — (1.08 Ash + ²² / ₄₀ S.)
MEIGS CREEK OR NO. 9 COAL						
53	Washington.....	2.95	12.89	5.55	12245	14946
52	Washington.....	3.40	9.58	5.03	12749	14970
44	Noble.....	3.06	12.33	6.00	12357	15011
45	Noble.....	2.90	10.16	4.27	12692	14895
43	Noble.....	2.55	11.41	5.79	12514	14918
42	Noble.....	3.12	12.85	5.60	12130	14827
50	Morgan.....	5.13	11.74	4.89	11925	15270
48	Morgan.....	5.05	10.37	4.30	12114	14621
49	Morgan.....	4.07	10.66	5.07	12202	14637
47	Noble.....	3.54	13.23	6.21	11956	14787
46	Noble.....	4.85	9.82	5.59	12301	14757
37	Belmont.....	4.47	13.07	3.27	12002	14870
40	Belmont.....	3.40	14.94	4.39	11840	14890
41	Belmont.....	3.52	11.84	3.67	12391	14947
39	Belmont.....	4.17	9.60	3.11	12602	14863
38	Belmont.....	4.31	11.68	1.94	12307	14888
36a	Belmont.....	7.52	11.24	2.11	11860	14846
36	Belmont.....	4.98	12.82	2.41	11974	14846
35	Harrison.....	5.35	10.29	2.20	12393	14919
	Av.....	4.11	11.60	4.28	12240	14845

APPENDIX B

TABLE 21

UNIT COAL VALUES

Compiled from Bulletins 261, 290, 332, United States
Geological Survey

State No.	Table No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis
			Moisture	Ash	Sulphur	B. t. u.	
							B. t. u. — 5000 S 1.00 — (1.08 Ash + $\frac{22}{40}$ S.)
ALABAMA							
1	1078M*	Walker.....	1.35	13.63	.71	12991	15509
1	1201C *	Walker.....	2.34	12.54	.72	12856	15313
2	1075M	Walker.....	2.25	9.04	1.09	13133	14967
2	1076M	Walker.....	2.42	11.13	1.10	12695	14879
2	3011M	Walker.....	4.71	10.17	1.33	12596	14992
2	1225C	Walker.....	3.36	12.43	1.01	12350	14879
2	3211C	Walker.....	3.95	14.59	1.12	11785	14722
3	3018M	Bibb.....	3.03	10.72	.49	13034	15285
3	3255C	Bibb.....	2.72	14.36	.55	12461	15263
4	3034M	Bibb.....	3.67	3.14	1.22	14396	15536
4	3103C	Bibb.....	6.43	12.92	1.08	12395	15616
5	4091M	Blount.....	2.93	2.73	.65	14693	15636
5	4252C	Blount.....	5.59	16.08	1.40	11906	15518
6	4293M	Jefferson.....	2.81	3.51	.59	14643	15701
5	4338C	Jefferson.....	3.23	6.71	.61	14074	15747
ARKANSAS							
1	1045M	Sebastian.....	1.02	7.49	1.10	14434	15927
1	2585M	Sebastian.....	3.53	7.77	1.29	14017	15971
1	1114C	Sebastian.....	3.24	12.61	1.24	13129	15846
1	2689C	Sebastian.....	7.49	17.97	1.06	11369	15604
2	1049M	Sebastian.....	.95	6.97	2.12	14387	15806
2	1160C	Sebastian.....	2.23	9.20	1.87	13750	15733
3	1115M	Sebastian.....	1.60	7.91	1.42	14162	15818
3	1296C	Sebastian.....	2.19	11.63	1.28	13464	15849
5	1130M	Franklin.....	1.38	6.95	1.52	14330	15790
5	1331C	Franklin.....	2.36	12.08	1.99	13259	15761
7	2593M	Sebastian.....	3.97	5.91	1.53	14236	15945
7	2688C	Sebastian.....	5.47	11.69	2.02	12690	15582
7	2722C	Sebastian.....	6.89	15.00	2.24	12060	15787
8	2587M	Johnson.....	3.12	8.46	1.84	13793	15797
8	2744C	Johnson.....	5.19	14.01	2.05	12460	15731
9	2599M	Sebastian.....	1.99	7.06	1.05	14087	15628
9	2690C	Sebastian.....	5.26	24.81	1.00	10451	15434
10	2647M	Ouachita.....	39.50	12.58	.53	5877	12551
10	2726C	Ouachita.....	39.43	9.71	.49	6356	12717
13	3798M	Franklin.....	2.91	17.51	3.12	12312	15898
13	4626C	Franklin.....	1.76	14.96	2.29	12926	15853

* Samples marked M are mine samples; those marked C are car samples of various sizes of coal.

TABLE 21
UNIT COAL VALUES—(Continued)

State No.	Table No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis	
			Mois- ture	Ash	Sul- phur	B. t. u.	B. t. u. — 5000 S 1.00 — (1.08 Ash + ²² / ₄₀ S.)	
CALIFORNIA								
1	1607M	Alameda.....	18.02	16.37	3.07	8105	12699	
1	1680C	Alameda.....	18.51	15.49	3.05	8507	13243	
COLORADO								
1	1383M	Boulder.....	20.02	3.61	.52	10237	13477	
1	1523C	Boulder.....	18.68	5.99	.55	10143	13570	
FLORIDA								
1	3270C	Orange.....	21.00	5.17	.45	8127	11076	
GEORGIA								
1	4156M	Chattanooga...	2.85	7.84	.67	14198	16039	
1	4320C	Chattanooga...	3.80	14.49	1.27	12791	15939	
ILLINOIS								
24	2854M	Clinton.....	13.43	9.18	3.35	10937	14395	
24	2972C	Clinton.....	11.44	10.71	4.94	10958	14422	
25	2856M	Clinton.....	11.64	8.66	3.41	11290	14416	
35	2991C	Clinton.....	11.35	13.40	4.76	10733	14666	
23	4385M	Clinton.....	15.06	9.65	1.05	10726	14435	
10	1648C	Franklin.....	9.50	11.44	1.45	11506	14783	
13	1694M	Franklin.....	9.46	8.12	1.63	11990	14745	
13	1786C	Franklin.....	8.31	10.48	1.55	11727	14651	
19	1871M	Franklin.....	9.90	7.74	.48	12001	14699	
19	1926C	Franklin.....	14.91	8.93	.52	10958	14545	
19	2020C	Franklin.....	10.72	9.36	.91	11686	14800	
18	1741M	La Salle.....	13.87	10.31	3.44	10985	14790	
18	1779C	La Salle.....	12.39	8.92	3.92	11399	14784	
26	3003	Logan.....	15.68	12.09	3.51	10215	14482	
9	1625M	Macoupin.....	13.29	8.90	4.12	11162	14641	
9	1635C	Macoupin.....	13.54	10.74	4.03	10807	14599	
9	1639C	Macoupin.....	13.72	10.32	3.96	10870	14627	
9	4247C	Macoupin.....	15.25	15.35	3.81	9790	14528	
20	2731C	Macoupin.....	14.68	13.68	3.88	10053	14409	
4	1341M	Madison.....	15.09	7.42	.83	11151	14533	
4	1417C	Madison.....	12.91	11.64	1.32	10804	14552	

TABLE 21
UNIT COAL VALUES—(Continued)

State No.	Table No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis B. t. u. — 5000 S 1.00 — (1.08 Ash + ²² / ₄₀ S.)
			Mois- ture	Ash	Sul- phur	B. t. u.	
5	1556C	Madison.....	17.02	16.79	3.29	9319	14523
7	1609M	Madison.....	11.87	11.58	4.75	10768	14425
7	1611C	Madison.....	11.46	17.31	4.40	10026	14542
7	1780C	Madison.....	10.83	13.18	4.53	10816	14618
21	2770M	Madison.....	15.23	9.03	1.59	10901	14595
21	2852C	Madison.....	15.54	10.93	1.38	10507	14517
22	2772M	Madison.....	13.51	10.15	4.01	10881	14566
22	2905C	Madison.....	11.91	13.01	5.34	10615	14554
22	2896C	Madison.....	13.03	14.53	4.35	10192	14480
23	2774M	Madison.....	13.07	10.06	3.59	10949	14535
23	2819C	Madison.....	13.47	11.53	4.41	10510	14360
23	2803C	Madison.....	15.68	15.59	3.98	9655	14483
29	3911M	Madison.....	14.25	9.44	3.72	10892	14566
29	3913M	Madison.....	12.69	8.76	3.62	11236	14571
29	3958C	Madison.....	12.47	12.56	4.37	10667	14602
29	3963C	Madison.....	13.10	16.00	4.17	9983	14519
29	3980C	Madison.....	12.25	12.33	4.42	10719	14578
15	1725M	Marion.....	10.25	12.53	3.70	11077	14683
15	1761C	Marion.....	9.95	13.23	3.87	10960	14622
6	1449M	Montgomery..	14.89	7.87	3.61	11016	14518
6	1661M	Montgomery..	12.90	11.08	3.78	10856	14602
6	1557C	Montgomery..	14.43	13.28	4.01	10064	14290
6	1702C	Montgomery..	11.93	14.18	4.29	10303	14332
8	1627C	Montgomery..	13.20	12.53	4.47	10514	14673
1	1095M	St. Clair.....	11.17	10.32	4.22	11223	14612
1	1261C	St. Clair.....	9.75	13.20	4.10	11025	14675
2	1152C	St. Clair.....	12.03	22.44	4.00	9149	14542
30	3912M	St. Clair.....	9.88	10.81	3.83	11439	14733
30	4364C	St. Clair.....	11.69	13.19	4.38	10699	14625
31	4251M	St. Clair.....	14.38	8.75	3.13	10858	14375
31	4376C	St. Clair.....	13.10	13.25	3.66	10363	14423
14	1704M	Sangamon.....	13.89	11.26	3.83	10636	14540
14	1740C	Sangamon.....	12.77	11.78	4.16	10757	14607
27	2897M	Sangamon.....	14.29	8.18	4.41	11007	14488
27	3052C	Sangamon.....	16.00	13.77	4.05	9940	14554
34	4414M	Saline.....	7.51	7.48	1.58	12686	15091
34	4636C	Saline.....	9.33	11.89	2.76	11572	14984
34	4622C	Saline.....	7.81	8.38	2.36	12418	15029
3	1170M	Williamson....	7.50	7.15	.99	12386	14646
3	1318C	Williamson....	8.50	11.28	1.72	11776	14916
11	1634M	Williamson....	8.30	9.26	2.82	11999	14794
11	1654C	Williamson....	7.76	10.61	1.97	11957	14835
11	1660C	Williamson....	8.86	11.66	2.46	11702	14956
11	1718C	Williamson....	8.61	7.66	1.65	12236	14797
12	1683M	Williamson....	8.29	10.83	2.81	11837	14867
12	1762C	Williamson....	8.20	12.95	3.48	11362	14740

TABLE 21
UNIT COAL VALUES—(Continued)

State No.	Table No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis B. t. u. — 5000 S 1.00 — (1.08 Ash + ²² / ₄₀ S.)
			Mois- ture	Ash	Sul- phur	B. t. u.	
12	4201C	Williamson	15.87	9.52	2.34	10784	14701
12	3907C	Williamson	12.61	10.50	2.37	11066—	14647
12	4085C	Williamson	15.31	10.47	2.32	10820	14846
16	1731M	Williamson	9.37	7.37	1.25	12058	14632
16	1820C	Williamson	8.43	9.60	1.14	11959	14772
28	3629M	Williamson	8.72	7.62	1.00	12200	14727
28	3789C	Williamson	7.78	9.98	1.32	11959	14770
INDIANA							
20	3536M	Clay	15.38	5.88	1.95	11680	15004
20	3979C	Clay	16.91	17.37	1.89	9524	14900
15	3473M	Greene	13.53	7.55	.95	11738	15028
15	3567C	Greene	13.58	8.15	.91	11419	14749
16	3564C	Greene	10.30	11.75	4.23	11218	14737
17	3516M	Knox	10.60	8.30	3.69	11752	14754
17	3981C	Knox	12.08	11.02	3.65	11011	14630
10	1853M	Parke	11.54	9.62	4.41	11655	15116
10	1979C	Parke	10.72	8.57	3.83	11767	14857
19	3534M	Parke	13.70	5.91	2.66	11930	15036
7	1824M	Pike	10.18	8.12	3.96	12181	15193
7	1881C	Pike	8.90	9.21	3.74	12008	14946
7	1882C	Pike	11.12	9.35	3.78	11549	14811
12	2701M	Pike	11.29	6.87	3.09	11921	14772
12	2759C	Pike	10.57	11.65	3.87	11266	14818
18	3525M	Pike	12.88	6.14	1.70	11801	14728
18	3801C	Pike	11.13	6.98	1.64	12031	14856
1	1410M	Sullivan	13.25	9.16	1.87	11360	14857
1	1507C	Sullivan	11.40	13.40	2.50	11061	15032
4	1775M	Sullivan	14.86	7.35	2.26	11324	14759
4	1844C	Sullivan	13.99	14.32	2.31	10318	14730
5	1773M	Sullivan	12.14	8.96	3.54	11516	14875
5	1859C	Sullivan	12.03	10.88	4.27	11192	14726
6	1772M	Sullivan	10.45	9.58	4.04	11745	14995
6	1875C	Sullivan	10.80	12.62	4.39	11185	14990
11	1883M	Sullivan	14.23	5.72	.89	11722	14764
11	2087C	Sullivan	12.15	8.14	1.41	11761	14934
8	1828M	Vigo	10.68	12.24	4.38	11261	14984
8	2037C	Vigo	9.55	10.61	3.72	11759	15042
9	1848M	Vigo	13.73	8.65	3.00	11360	14891
9	1960C	Vigo	13.53	10.76	3.15	10948	14759
9	1973C	Vigo	12.82	10.30	3.27	11119	14752
13	3467M	Vigo	13.43	7.34	2.16	11448	14642
13	3748C	Vigo	12.97	12.09	3.18	10899	14871
14	3491M	Vigo	13.62	7.11	3.28	11543	14797
14	3775C	Vigo	7.88	14.20	5.14	11146	14725

TABLE 21
UNIT COAL VALUES—(Continued)

State No.	Table No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis B. t. u. — 5000 S 1.00 — (1.08 Ash + ²² / ₄₀ S.)
			Mois- ture	Ash	Sul- phur	B. t. u.	
2	1425M	Warrick.....	9.28	9.34	4.44	11799	14806
2	1495C	Warrick.....	9.62	13.02	4.43	11122	14754
3	1759M	Warrick.....	11.28	7.63	3.58	11792	14792
3	1941C	Warrick.....	13.18	15.63	4.79	10030	14547
Iowa							
1	1270M	Davis.....	11.35	10.51	4.72	11345	14871
1	1347C	Davis.....	8.24	16.00	5.03	11027	15026
2	1289M	Marion.....	15.65	11.64	5.10	10289	14548
2	1570C	Marion.....	14.21	15.22	4.66	10019	14652
3	1312M	Polk.....	14.42	10.99	5.89	10640	14680
3	1434C	Polk.....	13.88	14.01	6.15	10244	14698
4	1323M	Appanoose....	17.13	7.07	4.00	10931	14694
4	1437C	Appanoose....	14.08	10.96	4.26	10723	14650
5	1332M	Lucas.....	18.69	7.73	2.39	10505	14496
5	1433C	Lucas.....	15.39	12.63	3.19	10242	14567
INDIAN TERRITORY							
(Town)							
1	1059M	Henryetta....	8.87	8.63	1.62	12096	14848
1	1138C	Henryetta....	7.04	10.01	1.92	12202	14929
2	1071M	Hartshorne....	1.46	6.40	1.38	14040	15375
2	1184C	Hartshorne....	4.45	11.00	1.52	12607	15129
3	1080M	Edwards.....	2.93	10.30	3.73	12591	14786
3	1274C	Edwards.....	4.61	11.14	3.63	12319	14918
4	1151M	Lehigh.....	6.50	9.31	3.67	11842	14318
4	1470C	Lehigh.....	6.24	13.21	3.96	11228	14267
5	1481C	Lehigh.....	8.29	25.05	3.95	9110	14264
9	4020C	Panama.....	5.11	8.03	1.18	13662	15897
KANSAS							
(County)							
1	1018M	Crawford.....	2.91	9.55	3.79	12947	15063
1	1097C	Crawford.....	4.99	12.97	4.28	12242	15293
2	1017M	Crawford.....	2.44	10.60	5.63	13043	15373
2	1122C	Crawford.....	4.18	17.91	6.27	11642	15511
3	1037M	Cherokee.....	2.54	9.87	4.47	13340	15535
3	1086C	Cherokee.....	2.50	12.45	5.68	12900	15589
4	1473C	Atchison.....	6.95	12.19	8.04	11905	15244
5	1411M	Cherokee.....	5.11	8.90	4.34	12926	15332
5	1567C	Cherokee.....	4.10	10.54	3.77	12895	15412
6	2790M	Linn.....	11.13	12.60	2.41	11219	15011
6	2843C	Linn.....	9.04	15.72	3.72	11142	15231

TABLE 21

UNIT COAL VALUES—(Continued)

State No.	Table No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis	
			Mois- ture	Ash	Sul- phur	B. t. u.	B. t. u. — 5000 S	
							1.00 — (1.08 Ash + ²² / ₄₀ S.)	
KENTUCKY								
1	1321M	Bell.....	2.91	3.53	.89	14322	15280	
1	2350M	Bell.....	3.42	3.18	1.53	14375	15491	
1	1474C	Bell.....	3.10	4.39	1.22	14148	15397	
1	2445C	Bell.....	5.21	8.22	1.12	13214	15427	
2	1365M	Hopkins.....	8.49	7.10	3.53	12344	14858	
2	1461C	Hopkins.....	7.91	9.13	3.62	12200	14979	
3	1367M	Hopkins.....	7.98	9.30	4.03	11965	14748	
3	1506C	Hopkins.....	7.92	10.06	3.52	12022	14944	
4	1382M	Webster.....	4.61	7.40	3.33	12861	14836	
4	1539C	Webster.....	5.27	14.18	4.54	11950	15240	
5	2270M	Harlan.....	4.32	2.28	.48	14121	15165	
5	2528C	Harlan.....	4.36	3.70	.67	13923	15217	
6	2405M	Johnson.....	6.95	2.03	.48	13687	15054	
6	2592C	Johnson.....	5.12	2.76	.57	13743	14975	
7	2453M	Muhlenberg....	8.76	9.42	4.07	11965	14919	
7	2595C	Muhlenberg....	8.47	9.48	3.60	11986	14886	
8	3678M	Union.....	7.46	4.60	.97	13489	15443	
8	3860C	Union.....	5.46	7.92	1.18	13239	15444	
9	3722M	Ohio.....	10.03	7.67	2.56	12076	14758	
9	3723M	Ohio.....	9.89	8.69	2.45	11927	14872	
9	3865C	Ohio.....	8.70	8.96	3.14	12078	14922	
MARYLAND								
1	2018M	Garrett.....	2.47	9.55	1.23	13853	15936	
1	2274C	Garrett.....	2.33	13.13	1.49	13255	15942	
MISSOURI								
1	1043M	Bates.....	4.92	14.52	5.34	11992	15334	
1	1126C	Bates.....	8.33	19.36	5.25	10586	15209	
2	1226M	Macon.....	14.74	7.78	3.79	11185	14705	
2	1348C	Macon.....	11.50	16.86	5.16	10179	14709	
3	1549C	Putnam.....	15.71	20.78	3.69	8840	14471	
4	1446M	Morgan.....	13.34	6.91	5.06	11605	14855	
4	1516C	Morgan.....	12.67	4.83	5.12	12487	15426	
5	2795M	Randolph.....	13.38	10.02	4.48	11084	14808	
5	2865C	Randolph.....	12.92	13.62	5.03	10548	14793	
6	2817M	Randolph.....	14.01	10.29	5.23	11030	14955	
6	2904C	Randolph.....	13.80	11.74	5.60	10796	14929	
7	2823M	Adair.....	17.19	9.28	2.76	10598	14677	
7	2936C	Adair.....	16.36	19.51	3.53	9007	14566	
7	2942C	Adair.....	17.30	23.38	2.94	8240	14496	
7	2937C	Adair.....	16.39	20.18	3.12	8946	14626	
10	4197M	Macon.....	15.41	11.61	3.78	10582	14853	
10	4257C	Macon.....	15.23	20.50	3.69	9099	14712	

TABLE 21
UNIT COAL VALUES—(Continued)

State No.	Table No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis
			Moisture	Ash	Sulphur	B. t. u.	
							B. t. u. — 5000 S 1.00 — (1.08 Ash + ²² / ₄₀ S.)
MONTANA							
1	1298C	Carbon.....	11.05	10.97	1.73	10539	13727
2	4234C	Carbon.....	8.51	15.39	.60	10478	14017
3	4271C	Carbon.....	8.56	13.39	.54	10685	13899
NEW MEXICO							
1	(1025)M						
	(1026)M	McKinley.....	10.96	4.01	.52	11885	14048
1	1278C	McKinley.....	12.29	6.99	.63	11252	14058
2	1028M	McKinley.....	9.68	8.08	1.55	11623	14301
2	1307C	McKinley.....	10.79	18.66	1.26	9907	14398
3	3221M	Colfax.....	2.50	9.13	.72	13127	15006
3	3295C	Colfax.....	3.45	16.67	.73	11893	15173
3	3307C	Colfax.....	4.36	15.92	.83	11912	15220
3	3308C	Colfax.....	2.75	15.52	.64	12166	15141
4	3228M	Colfax.....	2.19	11.11	.57	13063	15246
4	3331C	Colfax.....	2.78	14.57	.61	12294	15113
4	3315C	Colfax.....	3.38	13.54	.61	12445	15202
5	3226M	Colfax.....	2.25	12.37	.75	13030	15472
5	3294C	Colfax.....	2.72	14.57	.69	12539	15408
NORTH DAKOTA							
1	1971M	Stark.....	42.06	7.66	1.13	6158	12441
1	1279C	Stark.....	35.38	9.35	1.55	6923	12756
1	2289C	Stark.....	32.64	11.42	3.54	6970	12798
2	1730M	Williams.....	41.13	5.36	.72	6485	12242
2	1416C	Williams.....	36.78	5.09	.48	7204	12496
2	2365C	Williams.....	36.13	5.04	.59	7326	12558
3	1935M	McLean.....	40.53	5.05	.76	6644	12325
3	2243C	McLean.....	35.96	7.75	1.15	7069	12740
OHIO							
6	2095M	Belmont.....	3.99	8.07	3.49	13102	15144
6	2392C	Belmont.....	5.31	8.52	3.33	12843	15153
11	3986M	Belmont.....	4.13	7.96	4.12	13088	15155
11	4157C	Belmont.....	3.44	12.94	4.32	12287	15049
12	4151C	Belmont.....	4.14	9.38	3.96	12874	15172
12	4178C	Belmont.....	2.97	9.97	3.65	12933	15133
7	2090M	Guernsey.....	6.28	7.30	3.55	12701	14930
7	2656C	Guernsey.....	6.65	10.55	3.13	12179	14984

TABLE 21

UNIT COAL VALUES—(Continued)

State No.	Table No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis
			Mois- ture	Ash	Sul- phur	B. t. u.	B. t. u. — 5000 S 1.00 — (1.08 Ash + ²² / ₄₀ S.)
1	1896M	Jackson.....	8.45	6.73	3.10	12249	14647
1	2071C	Jackson.....	7.71	11.95	4.61	11515	14685
2	1898M	Jackson.....	9.38	7.62	4.08	11898	14590
2	2109C	Jackson.....	9.01	11.34	4.02	11495	14758
4	1910M	Jefferson.....	4.06	7.75	3.67	13147	15152
4	2083C	Jefferson.....	3.53	9.12	3.47	13072	15226
5	1944M	Jefferson.....	4.69	6.01	1.54	13325	15060
5	2062C	Jefferson.....	4.34	7.30	1.72	13178	15078
3	1900M	Perry.....	10.78	6.13	1.11	11993	14563
3	2144C	Perry.....	9.90	11.58	1.81	11277	14605
8	2119M	Perry.....	8.92	5.85	3.00	12328	14653
8	2559C	Perry.....	7.55	8.37	2.84	12128	14644
10	3969M	Tuscarawas....	4.46	8.54	3.73	12845	15022
10	4059C	Tuscarawas....	4.49	7.53	2.93	12958	14938
9	2208M	Vinton.....	6.79	7.66	3.34	12514	14858
9	2310C	Vinton.....	5.59	8.29	3.15	12773	15068
9	2311C	Vinton.....	8.10	11.93	3.35	11563	14766

PENNSYLVANIA

10	2080M	Allegheny.....	3.67	5.46	1.37	13874	15395
10	2229C	Allegheny.....	2.61	6.17	1.26	13997	15475
13	3437M	Allegheny.....	2.53	8.98	2.21	13356	15303
13	3879C	Allegheny.....	2.65	13.16	2.16	12816	15507
8	2014M	Cambria.....	3.49	5.71	.95	14515	16108
8	2152C	Cambria.....	3.51	6.63	.94	14279	16025
16	4029M	Cambria.....	2.74	7.23	1.51	14144	15876
16	4169C	Cambria.....	4.25	7.87	1.59	13513	15553
18	4348M	Cambria.....	2.66	8.56	2.97	13995	16014
18	4509C	Cambria.....	4.46	8.47	1.49	13682	15903
21	4412M	Fayette.....	2.82	7.37	1.22	13991	15731
21	4609C	Fayette.....	5.13	8.71	.86	13365	15675
15	4027M	Indiana.....	2.84	8.27	3.11	14079	16094
15	4082C	Indiana.....	3.13	9.81	3.77	13795	16159
15	4104C	Indiana.....	2.57	10.33	3.97	13712	16072
17	4337	Indiana.....	2.22	8.42	1.54	13801	15624
17	4421	Indiana.....	4.35	11.90	1.51	12964	15725
9	2016M	Somerset.....	2.63	10.21	2.05	13705	15963
9	2199C	Somerset.....	3.09	11.33	2.04	13424	15945
5	1966M	Washington....	3.01	4.83	.73	14197	15499
5	2068C	Washington....	2.46	6.05	.88	14013	15430
11	3421M	Washington....	2.50	5.34	1.14	14146	15465
11	3532C	Washington....	1.95	7.29	1.18	13775	15320
12	3441M	Washington....	2.60	5.63	1.19	14184	15689
12	4098C	Washington....	1.96	9.25	2.19	13622	15560

TABLE 21
UNIT COAL VALUES—(Continued)

State No.	Table No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis
			Mois- ture	Ash	Sul- phur	B. t. u.	B. t. u. — 5000 S 1.00 — (1.08 Ash + ²² / ₄₀ S.)
4	1942M	Westmoreland..	2.73	9.13	1.33	13613	15629
4	2187C	Westmoreland..	3.15	10.41	1.26	13406	15714
6	1968M	Westmoreland..	4.08	9.50	1.64	13268	15557
6	2161C	Westmoreland..	3.24	12.52	1.94	12879	15555
7	1994M	Westmoreland..	3.30	11.18	1.79	13378	15887
7	2154C	Westmoreland..	4.09	12.47	2.08	13153	16050
19	4352M	Westmoreland..	2.01	6.32	1.39	14152	15579
19	4489C	Westmoreland..	3.39	8.36	1.05	13699	15685
20	4350M	Westmoreland..	2.48	9.24	3.03	13822	15936
20	4517C	Westmoreland..	4.00	10.54	2.85	13347	15899
22	4498C	Westmoreland..	3.98	10.16	1.00	13311	15693

TENNESSEE

1	2907M	Claiborne.	3.71	4.74	1.28	13804	15195
1	3016C	Claiborne.....	4.81	11.15	1.58	12569	15180
2	2931M	Campbell.....	3.61	3.41	.83	14130	15271
2	3129C	Campbell.....	5.09	6.81	.98	13295	15222
3	2929M	Campbell.....	4.25	4.13	.93	13666	15004
3	3040C	Campbell.....	5.38	7.05	.99	13048	15033
4	2956M	Roane.....	3.25	6.61	.85	13514	15112
4	3058C	Roane.....	6.39	9.53	.98	12578	15135
5	2958M	Morgan.....	2.25	6.91	2.96	13851	15456
5	3050C	Morgan.....	5.59	9.76	3.23	12841	15445
6	2977M	Cumberland....	3.80	4.50	.78	14182	15557
6	3102C	Cumberland....	3.89	14.43	.78	12514	15574
7	2979M	Fentress.....	3.46	9.08	2.42	12983	15073
7	3133C	Fentress.....	3.03	12.85	3.26	12602	15300
8	3005M	White.....	3.01	10.76	3.42	13104	15490
8	3127C	White.....	2.63	13.42	4.38	12715	15529
8	3128C	White.....	3.12	14.12	4.74	12517	15540
9	2995M	Grundy.....	3.44	9.21	.73	13219	15292
9	3113C	Grundy.....	3.92	14.09	.94	12508	15510
9	3114C	Grundy.....	5.68	18.55	.74	11480	15489
9	3115C	Grundy.....	4.68	9.26	.65	13163	15454
10	3009M	Marion.....	3.31	13.11	1.30	12193	15825
11	3471C	Cumberland....	3.53	27.87	.90	10264	15514

TEXAS

1	1196M	Houston.....	33.50	10.75	.56	7142	13034
1	1456C	Houston.....	34.70	11.20	.79	7056	13298
2	1241M	Wood.....	28.86	7.92	.50	7996	12794
2	1597C	Wood.....	33.71	7.28	.53	7348	12594

TABLE 21
UNIT COAL VALUES—(Continued)

State No.	Table No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis B. t. u. — 5000 S 1.00 — (1.08 Ash + ²² / ₄₀ S.)
			Moisture	Ash	Sulphur	B. t. u.	
3	2652M	Milan.....	36.01	7.38	.77	7132	12759
3	2734C	Milan.....	31.06	7.88	.99	7870	13059
4	2635M	Wood.....	36.80	6.25	.53	7101	12598
4	2717C	Wood.....	33.85	7.30	.51	7497	12885
UTAH							
1	3199C	Carbon.....	6.05	4.87	.55	13151	14848
2	3200M	Summitt.....	14.07	6.26	1.28	10471	13262
VIRGINIA							
1	2268M	Lee.....	5.69	8.11	2.31	13117	15428
1	2420C	Lee.....	4.06	4.73	1.20	13826	15267
2	2476C	Lee.....	3.35	5.58	.92	13932	15410
3	2382C	Wise.....	3.05	4.48	.67	14470	15736
4	2323M	Lee.....	3.89	3.06	.34	14144	15253
4	2358C	Lee.....	4.35	4.33	.79	13939	15353
5	4093M	Montgomery...	2.98	21.94	.68	11669	15949
5	4287C	Montgomery...	4.80	18.03	.63	11961	15825
5	4294C	Montgomery...	7.52	16.23	.65	11893	15900
6	4305M	Tazewell.....	2.60	4.48	1.35	14636	15867
6	4573C	Tazewell.....	5.62	9.79	1.21	13264	15880
WASHINGTON							
1	2456M	King.....	17.97	7.78	.43	10006	13604
1	2687C	King.....	16.04	11.53	.61	9938	13920
1	2686C	King.....	14.30	11.37	.72	10208	13930
2	2458M	Kittitas.....	3.39	10.39	.33	12847	15059
2	3098C	Kittitas.....	3.16	12.26	.38	12586	15070
WEST VIRGINIA							
6	1176M	Fayette.....	2.10	3.55	.75	14900	15870
6	1390C	Fayette.....	1.53	5.05	.65	14807	15944
7	1198M	Fayette.....	2.12	3.55	.90	14915	15895
7	1595C	Fayette.....	3.94	4.93	1.16	14382	15898
8	1257M	Fayette.....	1.90	4.87	.64	14452	15591
8	1515C	Fayette.....	4.16	7.17	.90	13786	15686
9	1208M	Fayette.....	1.98	3.76	.85	14738	15825
9	1561C	Fayette.....	4.08	6.58	.77	13925	15712

TABLE 21

UNIT COAL VALUES—(Continued)

State No.	Table No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis
			Moisture	Ash	Sulphur	B. t. u.	
							B. t. u. — 5000 S 1.00 — (1.08 Ash + $\frac{22}{40}$ S.)
13	1867M	Fayette.....	5.48	2.29	.79	14454	15734
13	2028C	Fayette.....	3.74	3.91	.89	14436	15721
14	1870M	Fayette.....	2.96	7.44	1.04	13972	15741
14	2004C	Fayette.....	5.09	3.27	1.03	14110	15480
19	2359M	Fayette.....	3.26	2.46	.78	14773	15733
19	2549C	Fayette.....	2.96	5.01	.89	14425	15780
2	1103M	Harrison.....	1.98	9.08	4.20	13466	15432
2	1308C	Harrison.....	1.95	7.86	3.48	13790	15536
15	2039M	Harrison.....	2.80	5.55	2.40	14105	15558
15	2195C	Harrison.....	2.01	8.55	2.54	13811	15664
20	2375M	Kanawha.....	2.66	4.44	1.14	14368	15571
20	2556C	Kanawha.....	2.82	8.03	1.38	13766	15609
21	2377M	Kanawha.....	3.57	3.62	1.14	14173	15362
21	2572C	Kanawha.....	3.57	4.85	1.32	13948	15346
22	3456M	Kanawha.....	2.75	5.49	.63	13813	15149
22	3457M	Kanawha.....	3.49	6.44	.63	13813	15449
22	3905C	Kanawha.....	3.42	7.82	.83	13486	15335
23	3458M	Kanawha.....	3.13	3.54	.59	13963	15027
23	3965C	Kanawha.....	2.05	8.10	1.35	13707	15420
23	3625C	Kanawha.....	3.25	7.58	1.22	13523	15317
25	4291M	Kanawha.....	3.91	7.68	.64	13471	15199
25	4360C	Kanawha.....	4.21	7.22	.64	13379	15229
11	1234M	McDowell.....	2.21	5.25	.44	14792	16075
11	1472C	McDowell.....	4.07	11.12	.51	13509	16122
12	1238M	McDowell.....	1.92	4.39	.52	14926	16013
12	1242M	McDowell.....	3.48	3.90	.73	14731	15989
12	1364C	McDowell.....	1.72	6.87	.68	14571	16065
1	1088M	Marion.....	1.40	6.67	1.59	14063	15447
1	1213C	Marion.....	1.75	6.34	.90	14107	15450
16	2041M	Marion.....	2.89	5.71	.69	14540	16020
16	2264C	Marion.....	5.57	8.37	1.20	13093	15701
10	1240M	Mercer.....	2.93	3.62	.48	14924	16039
10	1471C	Mercer.....	1.75	4.58	.56	15023	16125
18	2348M	Mingo.....	2.81	6.50	.66	13957	15504
18	2527C	Mingo.....	2.86	5.83	.67	14106	15554
3	1108M	Monongalia....	2.90	8.19	.75	13941	15829
3	1252C	Monongalia....	2.29	10.23	1.06	13558	15689
4	1116M	Preston.....	2.26	7.74	.85	13999	15697
4	2054M	Preston.....	3.57	6.21	.85	14218	15882
4	1262C	Preston.....	1.48	8.39	.90	14069	15764
4	2250C	Preston.....	3.91	10.11	1.07	13370	15744
17	2056M	Preston.....	3.22	7.33	1.73	13995	15822
17	2332C	Preston.....	3.46	8.12	1.45	13869	15861
5	1144M	Randolph.....	2.82	10.45	1.00	13475	15731
5	1297C	Randolph.....	1.45	10.10	.98	13718	15693

TABLE 21
UNIT COAL VALUES—(Concluded)

State No.	Table No.	COUNTY	ANALYSES OF COAL AS RECEIVED				"Unit Coal" Basis
			Mois- ture	Ash	Sul- phur	B. t. u.	B. t. u. — 5000 S
							1.00 — (1.08 Ash + ²² / ₄₀ S.)
WYOMING							
1	1368M	Sheridan.....	22.00	3.37	.60	9796	13192
	1479C	Sheridan.....	22.63	4.50	.59	9734	13444
2	1376M	Weston.....	8.60	21.90	4.94	9709	14550
	1571C	Weston.....	9.44	20.72	3.91	9650	14320
	2131C	Weston.....	8.93	20.79	4.03	10001	14757
3	1976M	Crook.....	17.74	11.55	7.03	9527	13918
	2278C	Crook.....	15.12	16.70	6.66	8928	13604
4	3160M	Carbon.....	12.32	5.19	.23	11102	13534
	3363C	Carbon.....	11.30	7.31	.28	10755	13316
	3396C	Carbon.....	12.40	6.77	.26	10706	13341
5	3164M	Sweetwater....	12.41	2.52	.80	11920	14071
	3213C	Sweetwater....	11.64	3.41	.81	11768	13923
6	3202M	Uinta.....	20.57	2.63	.51	10237	13383
	3390C	Uinta.....	19.00	3.12	.49	10307	13293
ALASKA							
2479	.....	.....	4.43	4.65	.51	13640	15083
2483	.....	.....	13.89	7.23	.82	12137	15537
2219	.....	.....	6.74	12.47	.44	11968	15017
2222	.....	.....	2.55	6.05	.57	13711	15101
2224	.....	.....	6.60	10.87	.41	11338	13898
2227	.....	.....	.90	4.90	.60	14868	15873
ARGENTINA, SOUTH AMERICA							
4079C	.....	.....	7.67	42.85	1.21	6320	13792
BRAZIL, SOUTH AMERICA							
172		Dry Coal.....	27.54	3.02	10028	14398	
173		Dry Coal.....	27.84	4.53	9830	14241	

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THE WEATHERING OF COAL

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AND

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I. INTRODUCTION¹

In February, 1908, there was published by the Engineering Experiment Station of the University of Illinois, Bulletin 17, entitled "The Weathering of Coal." This publication embodied the results of a series of experiments which were intended at the time to be introductory to an extended study of the subject. As was stated in the text (page 14), the experiments were of a preliminary nature, undertaken mainly to gain information for carrying out more elaborate and comprehensive tests. A number of circumstances made it evident to the writers of this bulletin that it would be advisable to make the work undertaken at that time of a purely preliminary nature; for example, it was decided to make use of relatively small samples, the amount being approximately 20 pounds each. It was thought that the indications given by these samples would serve the purpose of avoiding serious mistakes when tests upon larger masses were made. Moreover, while these experiments were in progress, data from another source accumulated, establishing the fact that a rapid deterioration occurred in the coal in the first few days after breaking out from the seam. This fact promised to have a very important bearing upon the changes which ordinarily would be attributed to weathering losses. This phase of the subject was carried out simultaneously by Mr. W. F. Wheeler and was included in the bulletin noted above under the title "Deterioration of Coal Samples." The effect of such deterioration was not established in time to incorporate the procedure indicated by the fact of such losses, in the experiments on the weathering samples. These fundamental reasons are sufficient to indicate the preliminary nature of the first bulletin. It has since been possible to continue the work in a far more satisfactory manner by making use of the experience already gained in the first experiments. The subject, as here presented again under the same title, has the justification, it is hoped, of being fairly well-rounded and complete in so far as is possible by making use of the experience and knowledge of modifying conditions available at the present time. In one phase of the subject, however, it is far from complete. The subject of weathering can not be gone into without involving also the subject of spontaneous combustion. It is along this latter line that the work is being continued, and it is hoped soon

¹ Credit is due Mr. W. F. Wheeler for the greater part of the work embodied in this bulletin. Mr. Wheeler died Nov. 18, 1909.

to bring those experiments to a stage where the results will justify their publication under that title.

II. COAL STORAGE

The storing of coal has become more and more of a necessity in the last few years, owing to market conditions, occasional labor difficulties at the mines and on the railroads, and the crowding of transportation facilities. Of these causes, the first is probably of chief importance. It is due to the variable demand for coal for domestic consumption, which necessitates either a much higher rate of production during the winter months or else the providing of sufficient storage capacity to carry over coal produced in the dull season. Especially is this true in the case of anthracite coal, which suffers the most from a variable demand owing to the fact that a larger proportion of it is used for domestic purposes. Anthracite requires much more expensive plants for its preparation than ordinary bituminous coal, and thus offers greater inducements for the operators to keep the rate of production near the capacity of their equipment. One means of doing this is by inducing the consumers to store coal in the summer months. The scheme at present used for this purpose is a sliding scale of prices with a fixed advance in price per ton for every month from April to September. This plan has worked admirably for a number of years, probably ten million tons of coal being stored each summer by consumers and coal dealers. The anthracite coal companies themselves have a combined storage capacity for about seven million tons, or approximately one tenth of the present annual production. This storage capacity is in very large units, the piles containing from 50 000 to 400 000 tons each.

The bituminous coal producers have a more uniform demand throughout the year for all sizes and grades of their product than the anthracite producers can expect. Large power plants, naval coaling stations and railroads are the principal interests storing bituminous coal, except around the great lakes. At nearly all the cities at the head of lakes, the coal companies themselves store great quantities of coal during the season of navigation. Part of this coal is for local consumption, but a larger part of it is for reshipment by rail.

While market conditions offer one of the principal reasons for storing coal, large manufacturing establishments, most power plants

and various other coal users feel compelled to have on hand a reserve supply that will enable their plants to run without interruption in case of strikes, car shortages and other unforeseen circumstances. For this purpose the amount of coal necessarily stored at different plants varies from a few hundred to a few thousand tons.

Anthracite is the nearest approach to an ideal coal for storage. It is practically unaffected by the weather. It is broken somewhat by handling, and at most of the larger storage plants it must be re-screened as it is reloaded. It is not subject to spontaneous ignition, and in consequence there is practically no limit to the size of the piles in which it can be stored. With bituminous coal, the case is different. Most bituminous coal will ignite spontaneously if placed in large enough piles; all of it suffers more or less disintegration during storage and rehandling. Only the coals least liable to fire and those that stand rehandling the best are stored to any extent by the coal producers. Many of the railroads, power plants, factories and naval coaling stations, however, are forced to store coal that is easily affected by the weather and subject to spontaneous ignition. The greatest losses due to coal storage are due to the firing of the stored coal. The atmospheric oxidation of the coal is going on slowly all the time at ordinary temperatures, and continues with increasing rapidity at higher temperatures, until in many cases it results in the ignition of the coal. Thus it must be seen that coals most readily oxidized by the air are most prone to spontaneous ignition, and are the ones that lose the most in heating value. Any heating of the coal in the pile represents just so much heat that will not be available later under the boiler. Most of the atmospheric oxidation does not produce any sensible heating, but it results, nevertheless, in an appreciable loss of heat units by the coal. The changes taking place in stored coal may be divided into two classes: (1) oxidation of pyrite, marcasite and other inorganic constituents; and (2) the direct oxidation of the organic matter of the actual coal. To the changes in the inorganic matter most of the visible changes are due,—the iron sulphide changes into sulphate of iron and sulphuric acid, the latter of which unites with the calcium and magnesium carbonates, almost invariably present in the coal, to form gypsum and magnesium sulphate. All such changes result in a large increase in volume and a marked disintegration of the coal, and they will also result in a considerable increase in the weight of the coal in many instances unless removed by the

leaching action of water. The other changes due to the direct oxidation of the coal substances cannot be detected by the eye except in rare instances where they have progressed nearly to completion, as in the case of a sample of coal taken from an outcrop in Peoria county, Illinois. (See Table 15). This particular coal has changed from a lustrous black bituminous coal to a dull brown lignite as far as appearances go. It is, however, the invisible change due to this direct oxidation of the carbon and available hydrogen of the coal substance and the absorption of the oxygen by unsaturated hydrocarbons that plays the principal part in promoting spontaneous ignition and in causing weathering losses in heating value.

III. HISTORICAL REVIEW

For the past fifty years, many chemists and engineers have been studying and observing the chemical and physical changes occurring in stored coal. Professor Grundmann¹ of Tarnowitz, Germany, published the first record of any extensive experiments to determine the weathering losses of coal. He made use of the percentage of ash in the coal to determine the change in weight that took place, and with that as a basis, decided that the coal in a pile of 300 tons lost 58 per cent in weight in a period of nine months, the greater portion of the loss taking place soon after the coal was placed in storage. Other experiments by the same writer show losses almost as great. Such changes are, however, hardly confirmed by his other observations, i. e., that the specific gravity and the composition of the coal substance, the actual coal, remained unchanged. It is almost a certainty that the explanation for his extreme figures is to be found in a lack of uniformity of the samples employed. The chief benefit derived from Grundmann's experiments comes from the interest which they aroused in the subject and the investigations they initiated.

Reder² at Ornabruck, Germany, was among the first to follow up Grundmann's work. Using the same kind of coal, he found a small increase in weight and no practical changes in the coal. In the case of one German coal, however, he found a loss of about 4 per cent in the calorific value. Professor Varrentrapp³ of Brunswick, Germany, worked at temperatures between 100° C. and 300° C. and found a

¹ Carnall's Ztsch. Vol. X, p. 236, 1862; Oest. Ztsch. f. Berg, u. Hütt Vol. XV, p. 270, 1867; Kerperly Bericht, 1866, p. 33.

² Oest. Ztsch. f. Berg, u. Hütt. Vol. XV, 1867; Reder, Ztsch. d. Ver. deutsch Eng Vol. X, p. 698, 1866.

³ Dingler's Jour. Vol. 175, p. 156; Vol. 178, p. 379, 1865.

very rapid oxidation of the coal. In three months at 284° C., coal was reduced completely to ash; and at 160° C., he claims to have oxidized more than one-half of the carbon in the same length of time. Present knowledge of the subject, however, would indicate that the temperature of the coal itself must have been considerably higher than 284° C. That would easily have been possible even though the temperature of the oven or containing vessel did not rise above that temperature. In our own experiments on spontaneous ignition, coal kept in an oven at 110° C. has oxidized rapidly enough to raise its own temperature nearly to 200° C. In experiments with coal under ordinary storage conditions, Varrentrapp reports losses in weight and calorific value of 33 per cent for coal exposed to the weather and 12 per cent for that kept under cover. The same coals are said to have lost 45 and 24 per cent respectively in value for gas making. From the lack of confirmation by subsequent work, it seems that improper sampling or some other error must be sought in explanation of the excessive losses reported.

In 1865, Fleck¹ analyzed a series of six German coals that had been in a cabinet for eleven years, exposed to the air. The samples were not uniform as regards ash contents, but on the ash and water-free coal, the samples all showed a small decrease in carbon and available hydrogen and an increase in oxygen. Richters² soon afterward investigated the action of oxygen on coal at ordinary and moderately raised temperatures. His conclusions are that the coal absorbs oxygen and gives off carbon dioxide and water in smaller amounts, thus leaving a portion of the oxygen combined with the coal substance, causing an increase in weight. The reaction was found to be more rapid at slightly raised temperatures, and it seemed to be unaffected by the amount of moisture present except that in the presence of pyrites the coal was more disintegrated and seemed more liable to heat. Richters found three different coals to lose as much as 3.6 per cent in calorific value in two weeks at about 80° C. He concludes that pyritic coals oxidize most when damp, and that coals free from pyrite are most affected if kept dry. Richters also placed several hundred pounds of fresh coal from different mines in baskets containing about one hundred pounds each, and buried these baskets in a large unprotected pile of coal. After about ten months' storage.

¹Technik d. Steinkohlen Deutschlands, Vol. II, p. 221, 1865.

²Dingler's Jour. Vol. 190, p. 398, 1868.

he found changes in weight varying from a loss of .5 per cent to a gain of 2.0 per cent in the various lots.

Professor Fischer ¹ of Gottingen comes to the same conclusion that was reached by Fleck and Richter, viz., that weathering and spontaneous ignition are due to oxidation of the coal substance and also of the pyrite and marcasite.

Groves and Thorp ² give practically a summary of the previous investigations as to the nature and extent of weathering, but they also ascribe part of the loss to the liberation of combustible occluded gases and state that serious explosions on coal-laden vessels have resulted from this source. They recommend the shipment of only lump coal as a means of preventing fires on shipboard.

E. C. Pechin ³ made analyses of Connelsville coke after two and five years' storage out of doors and found no changes. He states that the best anthracite will lose part of its carbon, and bituminous coal will lose from 10 to 25 per cent by weight upon exposure, but cites no data in proof of his statements. Professor J. W. Langley, in a discussion of the same paper, offers the opinion that the losses sustained by different types of coal during storage are proportional to their ignition temperatures. He mentions Grundmann's and Varrentrapp's experiments as proof.

R. L. Rothwell ⁴ says, as a result of practical observation, that there appears to be no loss in anthracite coal or eastern bituminous coal except in case of small sizes of bituminous coal. He also reviews Richters', Grundmann's and Varrentrapp's work.

R. S. Hale and H. J. Williams ⁵ report an investigation where they exposed three small samples of bituminous coal for eleven months and found a loss in calorific value of from one-half to one per cent. These samples were from Pennsylvania, Virginia and Maryland.

John Macauley, ⁶ general manager of the Alexandra Docks and Railway, Newport, England, comes to the conclusion, after making practical steaming tests with locomotives, that English coal depreciates from ten to twelve per cent per year in steaming value when stored in England. He states as his opinion that the loss in hot climates would be more nearly twenty-four per cent. If the coal were stored under water, less breakage would result; three per cent is esti-

¹Gas World, April 13, 1901.

²Chemical Technology, Vol. I, p. 82.

³Trans. Am. Inst. Min'g Engs., Vol. I, p. 286, 1872.

⁴Trans. Am. Inst. Min'g Engs., Vol. II, p. 150, 1873.

⁵Trans. Am. Soc. Mech. Engs., Vol. XX, p. 333, 1899.

⁶Prac. Eng., Oct. 2, 1903. Eng. (London), Oct. 30, 1903.

mated as being sufficient to cover the losses that would be sustained in one year. He bases his estimate for submerged coal on results obtained by burning coal recovered from wrecks, coal that had been under water continually for as long as ten years. There seems to be no certainty as to the original quality of the sunken coal, and such being the case, comparisons made with fresh coal can be only approximations.

Dr. James P. Kimball,¹ of Lehigh University, gives an excellent review of the work done by Grundmann, Varrentrapp, Richters and others, prior to 1879. He also goes thoroughly into the changes due to oxidation of pyrite and marcasite and considers that their effects have been underestimated. He thinks that the oxidation of marcasite especially is of as much importance as the oxidation of the coal itself. Several instances are given where good coking coal has lost its coking property on account of weathering action. Weathering of coal in the seam is mentioned, and analyses of coal from the Coalton or No. 7 seam in Kentucky are presented to show the extent of weathering due to exposure in the mine and also to lack of sufficient cover. As only the proximate analyses are given, together with the analyses of the soluble mineral matter, no material changes are made evident except an increased amount of sulphates of iron and calcium.

In an article by G. Arth,² a report is made of experiments with small coal stored in the air and under water. The conclusions given are that for a period of one year the changes in composition and calorific value are too small to receive practical consideration.

Several practical engineers consider that coal stored for use in locomotives loses from 10 to 50 per cent in heating value, but none of them presents data.

Practically all coal is stored in piles in the open air. The Western Electric Company³ at their Hawthorn plant in Chicago has, however, put in concrete-lined bins, or rather reservoirs, with a capacity of about 15 000 tons of coal. In these bins the coal is kept constantly submerged, primarily for protection from spontaneous ignition. Analyses of coal stored at this plant for two years both under water and in the open air show an advantage of 1.9 per cent in heating value in favor of the coal stored under water.

¹Trans. Am. Inst. Min'g Eng. Vol. VIII, p. 204, 1879.

²Bulletin Soc. Chem., Vol. XI. p. 619-622, 1894.

³Eng. News, Vol. 60, p. 729, 1908.

Several experiments have been made in the last few years by the coaling stations of the United States Navy and also the English Navy to determine the advantages, if any, to be obtained by storing coal under water, but as yet no reports of these experiments have come to our notice.

Dr. Habermann¹ states that the weathering and spontaneous ignition of coal are due to the property of the coal substance for absorbing oxygen. He gives the results of a series of experiments on spontaneous ignition where coal placed in a fire-brick retort at 50° C., and supplied with air at an ordinary temperature, practically ignited in forty-eight hours. Dr. Habermann also found great loss in gas making, coking and heating value.

An editorial in Power² gives Heidepin credit for showing that spontaneous ignition and weathering are due to direct oxidation of the coal substance and to the oxidation of pyrites, as Leibig supposed. Bunte also credits the phenomena to a direct oxidation and absorption of oxygen by the coal. The smaller sizes and the most porous coal are said to be affected the most. The absorption of oxygen may result in a gain in weight of as much as four per cent. W. A. Powers, chief chemist of the Santa Fe Railroad, in 1907, carried out an investigation of the weathering losses of the coals used on that road. These coals covered a wide range of country, samples being tested from Illinois, Missouri, Kansas, Colorado and New Mexico. One hundred-pound lots of coal were stored in the open air and under water for a period of seven months. The coal stored under water is said to have lost from .26 per cent to 5.92 per cent in weight, and from .56 per cent to 8.75 per cent in calorific value. The coal stored in the open air lost in weight .60 per cent to 4.78 per cent and 1.10 per cent to 9.40 per cent in calorific value.

E. A. Tessenden and J. R. Wharton³ state that the higher the percentage of volatile matter in a coal, the more prone it is to spontaneous ignition and the greater the weathering losses it will sustain. Occluded combustible gases, high sulphur content, small size, presence of moisture, high temperature, and free access of air are all given as causes of weathering and fires. Mention is made of the general schemes commonly employed for handling stored coal in open

¹Jour. Gasbel, Vol. 49, p. 419.

²Power, Vol. 27, p. 437, 1907.

³Bulletin University of Mo., Eng. Series, Vol. 1, 1908.

piles and in covered bins. They also note the plans used and proposed to reduce the liability of spontaneous ignition.

In their experimental work only one kind of coal, (from Staunton, Illinois) was used, but it was subjected to different storage conditions, namely, out of doors, in a warm dry room, and under water. Three sizes were prepared and used, making nine samples in all. The coal stored out of doors is said to have disintegrated badly, while that in water and in the dry room was not much damaged. Only the calorific value of the coal as sampled is made use of in determining the weathering losses. The results reported show the futility of trying to make accurate comparisons of the calorific values of fuels on an air-dry basis, with variable ash content. It seems practically certain that the exceedingly high losses found are due largely to discrepancies in the amounts of moisture and ash in the coal samples taken for analysis. Taking the average values for all of the samples used, the losses found in four months were 4.3 per cent for coal under water, 7.0 per cent for coal in dry rooms, and 14.1 per cent for exposed coal. Further experiments are being carried out on samples of Missouri coal, and in them the moisture and ash will be determined in addition to the calorific value.

In the fall of 1906, Mr. N. D. Hamilton,¹ under the direction of Professor S. W. Parr, began a preliminary series of experiments at the University of Illinois to determine the nature and amount of the chemical changes that take place in coal when it is exposed to the weather and also when it is more or less protected. This work extended over a period of nine months. The samples used were collected at the retail coal yards in Champaign and Urbana, Illinois. Most of the coal had been out of the mine for two weeks or more before sampling, time enough for material changes to have taken place, as will be shown later. There was some question as to the exact identity of the coal in the case of a few of the samples. The coal was not sampled and handled in such a manner as to make it representative of any particular product of the mines supplying it. However, that is of but slight importance, except that all of Mr. Hamilton's samples represent small coal and not lump coal, as was reported in some cases. It does not seem at all probable that the so-called lump coal would give the same results likely to be obtained on storing lump coal, as Mr. Hamilton broke the lumps up into pieces about one inch in diameter before storing. It seems very probable also that the

¹Bulletin 17, Eng. Exp. Sta., 1907.

changes taking place in such small lots of coal (about twenty pounds were used in each test), would be very much greater than would occur in actual storage practice, where it would be the exception to find a pile containing as little as two hundred tons. Mr. Hamilton's figures probably would represent only the outside layers of actual coal piles. If the coal in the storage pile becomes very warm, or ignites spontaneously, then the loss and chemical changes taking place may be in excess of changes in the small samples, but that will be the exceptional case. The various samples taken from the 20-lb. lots for analysis were not representative of even that small amount, as great variations occur in the ash and sulphur percentages reported.

In the last three investigations by Mr. Powers, Messrs. Tessen den and Wharton, and Mr. Hamilton, the Parr calorimeter was used exclusively, and probably it is responsible for some erroneous calorific values, owing to the effects of variable amounts of ash and sulphur on the rise in temperature observed in that instrument, some of which were not fully appreciated at the time. A study has been made recently¹ of these errors and it is now possible to correct for them with a fair degree of accuracy.

No account was taken of the amount of disintegration or of changes in weight during Mr. Hamilton's investigation. The tentative conclusions from his work were that coal stored dry or in the open would lose from 2 per cent to 10 per cent in calorific value in a period of nine months, the rate of loss being greatest at first. The coal stored under water did not lose appreciably in calorific value.

IV. STORAGE CONDITIONS

Object of the Experiments.—The object of these experiments was to determine the change in weight, the change in calorific value and the amount of disintegration that are liable to occur in the grades of coal found in Illinois and neighboring states under different conditions of storage, (1) in the open air in piles; (2) in covered bins; and (3) under water.

Source of Coal Tested.—The coal used in these experiments came entirely from Illinois mines. (1) For the principal series, coal from Vermilion, Sangamon and Williamson counties was used, as it was considered representative of about as great a difference in character as is shown by the coals of the State. The results on this series are

¹Jour. Am. Chem. Soc., Vol. 29, p. 1606, 1907.

embodied in Tables 1 to 12 inclusive. (2) Piles of coal of approximately 300 or 400 tons in amount from Christian and Fulton counties were available, and these were examined after they had been exposed for about six months. The results are shown in Table 13. (3) A 15-ton lot of Vermilion county coal had been piled on the ground for $2\frac{1}{2}$ years. Occasional analyses of it had been made and also of some of the same lot which had been stored under water in a barrel by Mr. Hamilton. This pile was resampled; the results of both analyses are embodied in Table 14. (4) A series of samples was taken from old pillars long exposed to mine conditions, as well as the more extreme case of an outcrop. These results are embodied in Table 15. (5) The Commonwealth Edison Company early in 1908, stored nearly 40 000 tons of coal from Williamson and Franklin counties. Advantage was taken of their offer to supply us with samples for experimental purposes. The results are embodied in Table 16.

Storage Conditions, Sizes of Coal and Sizes of Piles Employed.—

As was noted, the principal series consisted of car lots from representative mines in Vermilion, Sangamon and Williamson counties. Carloads of both screenings and nut coal were shipped to the University in January, 1908. One-half of each carload was piled out of doors to a uniform depth of about three and one-half feet, in shallow bins with earth floors. The other half carload was put in covered wooden bins, partly open on two sides, with board floors one and one-half feet above the ground. The coal filled these bins to a depth of about five feet. (See Fig. 1 and 2 for view of storage bins.) Facilities were not available for the storage of any large quantity of coal under water, and on that account only about one hundred pounds from each car was stored in this way. Stone-ware jars were used for containers. The jars, loosely covered to keep out the dust and to retard evaporation, were placed in the basement of the Chemistry building, where the temperature did not vary much from 70° F. The coal from Christian and Fulton counties was not inspected when it was stored, as it was not intended for experimental purposes. It was in piles three to seven feet in depth containing about 500 tons of screenings, entirely exposed to the weather. The coal stored by the Commonwealth Edison Company was in three piles, the main one containing about 25 000 tons of egg coal over three inches and less than six inches in diameter. The second pile contained 3500 tons of nut coal, and the third about 4500 tons of No. 1 washed coal. The

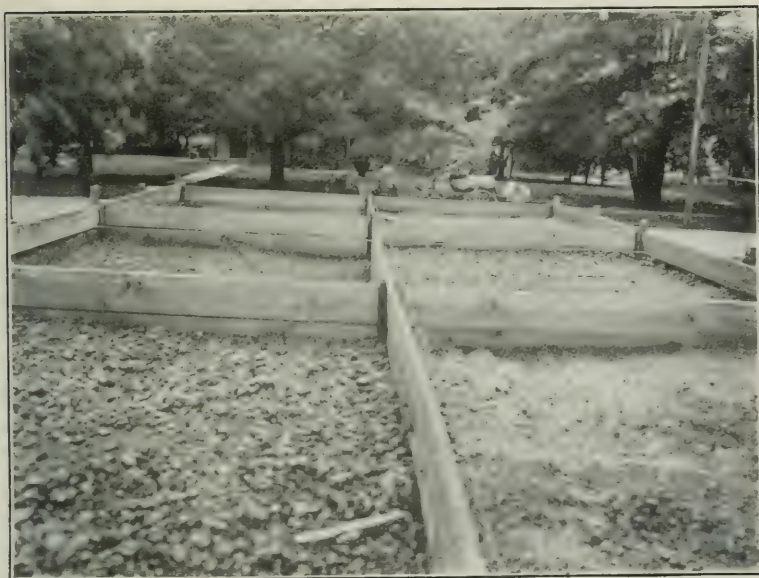


Fig. 1

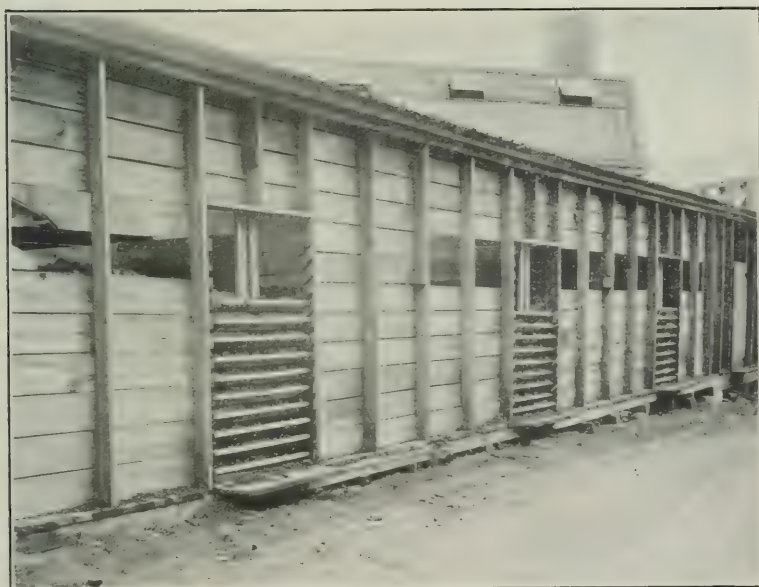


Fig. 2

pillar coal and that from the outcrop in Peoria county are all samples representing the entire thickness of the coal seam. The conditions and time of exposure are given in the tables following, (p. 15).

Sizing Tests.—It was thought that the amount of disintegration suffered by the coal would probably be one of the principal sources of loss, as it might change a coal of suitable size for use in a certain plant to a smaller size than could be used economically. When the coal was stored samples were screened to find the proportion of the various sizes from $\frac{1}{8}$ inch in diameter up to 1 inch and over. The screen used was of the revolving or trommel type, made of perforated steel plate. (See Fig. 3.)

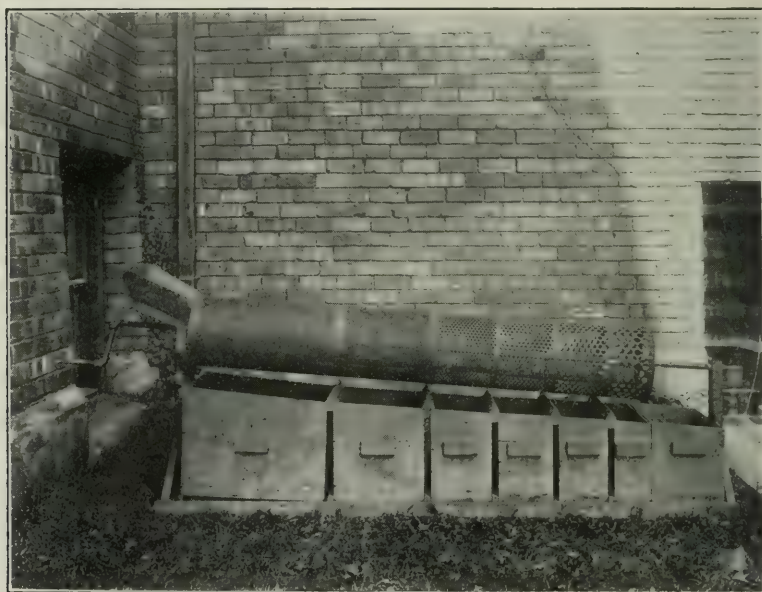


Fig. 3

The relative sizes of coal before and after storing for one and one-half years are shown in Tables 1 and 2 and also graphically in Fig. 4 and 5.

Explanation of Tables.—In the columns headed “per cent,” Tables 1 and 3, the figures represent the amount of coal between the two sizes given in the same line. The columns headed “cumulative

TABLE 1
SIZING TEST ON NUT COAL
Vermilion County, Illinois

Round Hole Screen		Original Sizes		Exposed Bins 1½ Years		Covered Bins 1½ Years	
Through inches	Over inches	per cent	Cumulative per cent	per cent	Cumulative per cent	per cent	Cumulative per cent
3	1	66.2	.....	42.5	.....	44.2	.....
1	¾	5.0	71.2	8.0	50.5	7.6	51.8
¾	½	7.2	78.4	11.8	62.3	11.7	63.5
½	⅜	4.0	82.4	6.9	69.2	6.7	70.2
⅜	¼	4.0	86.4	6.8	76.0	7.1	77.3
¼	⅛	5.0	91.4	10.9	86.9	10.4	87.7
⅛	0	8.6	100.0	13.1	100.0	12.3	100.0
Total.....		100.0	.....	100.0	.....	100.0	.....
Average diameter....		1.458 in.		1.074 in.		1.102 in.	

Williamson County, Illinois

3	1	94.0	.....	70.2	.....	68.5	.....
1	¾	1.6	95.6	5.7	75.9	5.7	74.2
¾	½	1.8	97.4	6.6	82.5	7.1	81.3
½	⅜	.7	98.1	3.1	85.6	4.1	85.4
⅜	¼	.5	98.6	3.2	88.8	3.6	89.0
¼	⅛	.5	99.1	4.6	93.4	4.9	93.9
⅛	0	.9	100.0	6.6	100.0	6.1	100.0
Total.....		100.0	.....	100.0	.....	100.0	.....
Average diameter....		1.910 in.		1.532 in.		1.506 in.	

Sangamon County, Illinois

3	1	89.4	.....	64.3	.....	52.0	.....
1	¾	4.1	93.5	6.9	71.2	9.3	61.3
¾	½	3.5	97.0	8.4	79.6	10.8	72.1
½	⅜	1.2	98.2	3.2	82.8	5.7	77.8
⅜	¼	.6	98.8	4.0	86.8	5.8	83.6
¼	⅛	.6	99.4	7.4	94.2	8.1	91.7
⅛	0	.6	100.0	5.8	100.0	8.3	100.0
Total.....		100.0	.....	100.0	.....	100.0	.....
Average diameter....		1.854 in.		1.442 in.		1.252 in.	

per cent" give the total amount of coal larger than the smaller of the two sizes given in that line.

The proportion of small sizes in the nut coal is shown to have increased considerably, and the average diameter to have decreased in proportion. The amount of coal that would pass a ½-in. hole

TABLE 2
SIZING TEST ON SCREENINGS
Vermilion County, Illinois

Round Hole Screen		Original Sizes		Exposed Bins 1½ Years		Covered Bins 1½ Years	
Through inches	Over inches	per cent	Cumulative per cent	per cent	Cumulative per cent	per cent	Cumulative per cent
1¾	1	19.0	.....	11.3	.....	11.6	.....
1	¾	8.9	27.9	6.3	17.6	6.3	17.9
¾	½	14.8	42.7	12.9	30.5	12.2	30.1
½	⅜	8.5	51.2	9.3	39.8	9.3	39.4
⅜	¼	11.1	62.3	11.8	51.6	11.8	50.2
¼	⅛	16.4	78.7	21.0	72.6	21.0	71.2
⅛	0	21.3	100.0	27.4	100.0	27.8	100.0
Total		100.0	.....	100.0	.....	100.0	.....
Average diameter		.548 in.		.425 in.		.425 in.	

Williamson County, Illinois

1¾	1	18.9	.....	19.0	.....	14.2	.....
1	¾	9.0	27.9	9.2	28.2	7.0	21.2
¾	½	14.4	42.3	15.4	43.6	13.0	34.2
½	⅜	8.5	50.8	9.5	53.1	9.0	43.2
⅜	¼	10.4	61.2	10.6	63.7	11.4	54.6
¼	⅛	15.4	76.6	17.0	80.7	20.2	74.8
⅛	0	23.4	100.0	19.3	100.0	25.2	100.0
Total		100.0	.....	100.0	.....	100.0	.....
Average diameter		.542 in.		.557 in.		.466 in.	

Sangamon County, Illinois

1¾	1	38.8	.....	15.1	.....	15.6	.....
1	¾	7.9	46.7	9.3	24.4	9.1	24.7
¾	½	13.2	59.9	15.6	40.0	15.6	40.3
½	⅜	6.6	66.5	7.7	47.7	9.7	50.0
⅜	¼	7.2	73.7	9.4	57.1	11.5	61.5
¼	⅛	11.2	84.9	17.2	74.3	19.6	81.1
⅛	0	15.1	100.0	25.7	100.0	18.9	100.0
Total		100.0	.....	100.0	.....	100.0	.....
Average diameter		.768 in.		.498 in.		.518 in.	

was nearly doubled in the case of the Vermilion county nut coal, and in the nut coal from Williamson and Sangamon counties there was seven times as much coal below ½ inch in diameter after one and one-half years' storage as there was originally. The average diameter

of the pieces of coal in all three of these lots was about three-fourths as great after storage as before, the average weight being only about four-tenths as great.

The changes in the screenings are not nearly so great as in the nut coal, but even then they are certainly of as much importance as any of the other changes due to weathering. The average diameter of the coal before and after weathering was calculated on the assumption that the diameter of the coal particles through any certain size of hole in the screen was the average of the diameter of that hole and of the one next smaller, i.e., the diameter of coal through the $\frac{1}{2}$ -in. screen and over the $\frac{3}{8}$ -in. screen was considered to be $\frac{7}{16}$ -in. There seems to be no advantage in favor of storage in either open or covered bins so far as the amount of disintegration shown by these experiments is concerned. The disintegration is due to the action of frost; to the opening of small cracks originally started at the time the coal was shot in the mine; and also to the oxidation of pyrite and marcasite, resulting in a large increase in volume, and consequently, a breaking up of the pieces of coal. With lump coal intended for sale or reshipment, this disintegration must result in a large decrease in value. While no sizing tests are available as proof, it seems probable from observation that coal kept absolutely dry, and not subjected even partially to the weather (as was that stored in covered bins), would not break up to the extent shown in these experiments. Probably the ideal way to store coal, so far as disintegration is concerned, would be under water, thus obviating the action of frost entirely. The friability of the coal after storage seems much increased, and any rehandling must result in much greater breakage than it would with freshly mined coal.

V. CHANGE IN WEIGHT

The storage of coal has been thought by some investigators to result in a considerable loss in weight. If the coal heats considerably and fires occur in the storage piles, there is undoubtedly a great loss in weight, but it is still an open question as to how great this change is in storage under fair average conditions. The change in the weight of air-dry or wet coal cannot be considered in this connection. The exact weight of dry coal must be ascertained by some means. The coal must be weighed, and then dried in an oven at some certain temperature for an exact determination of the amount of moisture

in it at the time, as it is not possible to get the coal into such an air-dry condition before and after storage that it will contain exactly the same percentage of moisture each time. The coal in these experiments was weighed, sampled carefully, and the moisture determined at 105° C. The weight of the moisture was then deducted from the weight of the air-dry coal, and the resulting weight of dry coal was used in making all comparisons. The results are given in Tables 3, 4 and 5. The larger samples (Table 3) show a loss of about one and one-half per cent in weight in two cases out of six, the other four show no change within the limits of experimental error, and it is doubtful whether even these two are not chargeable to possible discrepancies in moisture determinations rather than to any actual change in weight. The results of these experiments show only that any change in weight that does occur is very small in amount and is not to be considered unless the coal has heated considerably. Further data along this line are necessary, especially with large samples under actual storage conditions, before any conclusions as to either an increase or decrease in weight would be warranted.

TABLE 3
CHANGE IN WEIGHT OF COAL EXPOSED TO THE AIR

DESCRIPTION	Weight of Coal Dried at 105° C.	Weight of Coal Dried at 105° C.	Change in Weight	
Screenings from	pounds	pounds	pounds	per cent
Williamson Co., Ill.	Weighed Dec. 15, '08	Reweighed June 17, '09		
In open box on roof.....	311.8	307.0	-4.8	-1.54
In barrel in building.....	300.7	300.5	-0.2	-.07
Sangamon Co., Ill.	Nov. 27, '08	June 17, '09		
In open box on roof.....	227.7	224.4	-3.3	-1.45
In barrel in building.....	235.8	235.9	+0.1	+.04
Vermilion Co., Ill.	Nov. 11, '08	June 17, '09		
In open box on roof.....	289.0	288.9	-0.1	-.03
In barrel in building.....	284.0	284.9	+0.9	+.32

SIZING TEST ON NUT COAL
VERMILION COUNTY, ILL.

ORIGINAL SIZES

1 8.6	2 5.0	3 4.0	4 4.0	5 7.2	6 5.0	7 6.6 2		
EXPOSED BINS 1								
1 13.1		2 10.9		3 6.8	4 6.9	5 11.8	6 8.0	7 42.5
COVERED BINS 1								
1 12.3		2 10.4		3 7.1	4 6.7	5 11.7	6 7.6	7 44.2
WILLIAMSON COUNTY, ILL.								
ORIGINAL SIZES								
1 6.6	2 4.6	3 3.2	4 3.1	5 6.6	6 5.7	7 94.0		
EXPOSED BINS 1								
1 6.1	2 4.9	3 3.6	4 4.1	5 7.1	6 5.7	7 70.2		
COVERED BINS 1								
SANGAMON COUNTY, ILL.								
ORIGINAL SIZES								
1 5.8	2 7.4	3 4.0	4 3.2	5 8.4	6 6.9	7 64.3		
COVERED BINS 1								
1 8.3	2 8.1	3 5.8	4 5.7	5 10.8	6 9.3	7 52.0		
SIZES OF COAL-ROUND HOLE SCREEN								
0- ¹ / ₈ "	¹ / ₈ - ¹ / ₄ "	¹ / ₄ - ³ / ₈ "	³ / ₈ - ¹ / ₂ "	¹ / ₂ - ³ / ₄ "	³ / ₄ -1"	1'-3"		

¹ AFTER ONE AND ONE HALF YEARS' STORAGE

Fig. 4

SIZING TEST ON SCREENINGS VERMILION COUNTY, ILL

ORIGINAL SIZES

1 21.3	2 16.4	3 11.1	4 8.5	5 14.8	6 8.9	7 19.0
EXPOSED BINS ¹						
1 27.4	2 21.0	3 11.8	4 9.3	5 12.9	6 6.3	7 11.3
COVERED BINS ¹						
1 27.8	2 21.0	3 11.8	4 9.3	5 12.2	6 6.3	7 11.3
WILLIAMSON COUNTY, ILL						
ORIGINAL SIZES						
1 23.4	2 15.4	3 10.4	4 8.5	5 14.4	6 9.0	7 18.9
EXPOSED BINS ¹						
1 19.3	2 17.0	3 10.6	4 9.5	5 15.4	6 9.2	7 19.0
COVERED BINS ¹						
1 25.2	2 20.2	3 11.4	4 9.0	5 13.0	6 7.0	7 14.2
SANGAMON COUNTY, ILL						
ORIGINAL SIZES						
1 15.1	2 11.2	3 7.2	4 6.6	5 13.2	6 7.9	7 38.8
EXPOSED BINS ¹						
1 25.7	2 17.2	3 9.4	4 7.7	5 15.6	6 9.3	7 15.1
COVERED BINS ¹						
1 18.9	2 19.6	3 11.5	4 9.7	5 15.6	6 9.1	7 15.6

0 10 20 30 40 50 60 70 80 90 100 PER CENT

SIZES OF COAL - ROUND HOLE SCREEN

1 0-1/8"	2 1/8-1/4"	3 1/4-3/8"	4 3/8-1/2"	5 1/2-3/4"	6 3/4-1"	7 1-1 1/4"
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¹ AFTER ONE AND ONE-HALF YEARS' STORAGE

Fig. 5

TABLE 4
CHANGE IN WEIGHT OF COAL EXPOSED TO THE AIR

Lab. No.	DESCRIPTION	Weight of Coal Dried at 105° C. grams	Weight of Coal Dried at 105° C. grams	Gain in Weight grams	Gain in Weight per cent
	Screenings	Weighed Feb. 14, '08	Reweighed Nov. 17, '08		
1212	Williamson Co., Ill. . . .	Dry 1331	1348	17	1.28
1213	" " " " . . .	Wet ¹ 1222	1233	11	.90
1214	Sangamon " " " " . . .	Dry 1099	1114	15	1.36
1215	" " " " " " . . .	Wet ¹ 1121	1142	21	1.87
1216	Vermilion " " " " . . .	Dry 1021	1028	7	.69
1217	" " " " " " . . .	Wet ¹ 1056	1061	5	.47
	Nut Coal	Feb. 26 '08	Sept. 16, '08		
1219	Vermilion Co., Ill.	Dry 947	960	13	1.37
1221	Sangamon " " " "	" 1196	1222 ²	26	2.17
1223	Williamson " " " "	" 1138	1159	21	1.85
1220	Vermilion " " " " " " . . .	Wet 3130	3147	17	.54
1222	Sangamon " " " " " " . . .				
1224	Williamson " " " " " " . . .				

¹ Water evaporated and left coal dry for last month or six weeks. Considerable ferrous sulphate showed in all samples that had been wet, especially in Lab. No. 1215.

² This sample was reweighed Nov. 17, '08, instead of Sept. 16, '08.

TABLE 5
LOSS IN WEIGHT OF AIR-DRY COAL AT VARIOUS TEMPERATURES UP TO 260° C.

Lab. No.	Weight of Sample grams	TOTAL LOSS IN WEIGHT DUE TO HEATING IN AIR				
		1 hour at 105° C. per cent	4 hours at 105° C. per cent	18 hours at 140° C. per cent	14 hours at 260° C. per cent	44 hours at 260° C. per cent
1591 ¹	1	5.05	4.82	2.75	22.92	38.3
1592 ¹	1	5.65	5.45	2.96	25.00	Lost
1591	2	4.18	4.66	3.07	15.92	34.8
1592	2	4.71	5.08	3.36	14.60	34.3
1551	2	2.89	2.76	.22	19.40	31.3
1567	2	2.74	2.86	1.37	9.92	23.9
1569	1	6.23	6.20	3.66	24.55	48.1
1569	2	6.10	6.09	3.61	19.74	48.3
1569	3	5.95	6.18	4.07	22.89	45.2
1569	4	5.86	6.33	4.35	19.96	44.0
1402 ¹	1	17.90	....	....	51.10	63.8

¹ Size of coal 60 mesh, all other samples about 10 mesh.

A similar series of experiments (Table 4) was carried out on a small scale in the laboratory with coal of buckwheat size and smaller, both dry and under water. In about eight months every one of these samples showed a positive gain in weight, ranging from $\frac{1}{2}$ to 2 per cent. The coal kept under water showed the smallest average gain. The gain in weight of these samples was probably due to the absorption of oxygen by the coal substance and also to the oxidation of pyrite and marcasite. The gain in weight of bituminous coal upon heating for a short time at a moderate temperature is a phenomenon which has often been noted by chemists working with this substance. In this laboratory a number of air-dry samples were heated to various temperatures from 105° to 260° C. The figures representing the amount of moisture in the coal are given in the column headed "1 hour at 105° C.," Table 5. The same coals heated for four hours at the same temperature show changes in weight in both directions. The first two samples of finely pulverized coal both increased in weight. The 10-mesh samples in one and two-gram lots changed very little, three gaining and three losing in weight. The four portions of sample No. 1569 show the result of increasing the size of the sample without increasing in the same proportion the surface exposed to the air. The larger portions show a greater loss in weight because they do not have the opportunity to absorb so much oxygen on account of the smaller surface exposed. After 18 hours at 140° C., the losses are all smaller than enough to cover the amount of moisture present, thus indicating a gain in weight due to oxidation. The same relative changes in the four portions of sample No. 1569 are still evident. Heating at 260° C., however, causes a striking loss in weight due to the very rapid oxidation at that temperature which is approaching closely the ignition temperature of the coal. In fact, any quantity of coal of more than 100 grams, of the size used in these experiments, would be very apt to ignite if heated to 260° C.¹

Sampling.—The six cars of coal before mentioned were all inspected at the mine and sampled as they were loaded, to avoid any unknown changes while the coal was in transit. About four hundred pounds was taken at intervals with a scoop from the stream of coal as it comes from the chute, and this sample reduced by quartering to about two pounds, which was sent to the laboratory for immediate analysis. The next series of samples was taken about one week later

¹Eng. Exp. Sta., U. of I., Bul. 24, S. W. Parr and C. K. Francis, June, 1908.

when the coal was being hauled by wagon from the cars to the storage bins. Occasional shovelfuls were taken as the wagons unloaded, until a sample of about three or four hundred pounds was obtained. This was handled as before by alternate crushings and quarterings until only two pounds remained. At the laboratory this sample after air-drying was crushed to $\frac{1}{8}$ inch and smaller, and all further quartering was done with a riffle sampler. When the coal was once in place in the bins, it was thought best not to shovel it over or rehandle it in any way, as any extra handling would change the conditions from those of actual storage and would of course modify any results from sizing tests. To avoid this rehandling, a sampler was designed that would take cores through the whole thickness of the pile without disturbing any of the coal except that taken out as a sample. Ordinarily six cores, seven inches in diameter, were taken from a bin for a sample. This number of holes gave a sample of about 250 to 400 pounds, depending on the depth of the coal in any particular bin. The sampler itself (Fig. 4) is made up of two parts. One is a casing of spiral riveted pipe fitted with a notched shoe to overturn the larger pieces of coal that may be struck as it is forced into the pile. At the top it is protected by a stiffening ring to prevent battering of the pipe. The ring has 1-in. holes in opposite sides to admit the end of a bar or a small piece of pipe to be used as a handle to turn the large pipe, which will usually sink of its own weight, if rotated. This pipe serves only to prevent the coal from caving into the hole. The main part of the sampler is somewhat like a post-hole digger, except that it is fitted with a shutter at the bottom to retain the coal after being filled. It is used to remove the coal from the larger pipe as it is sunk. Casing and sampler are shown in Fig. 6.

VI. CHANGE IN CALORIFIC VALUE

The main part of the present investigation has been devoted to following the changes in calorific value of the actual coal substance. It is impossible to sample any lot of coal exactly as regards ash and sulphur, and for that reason it was found necessary to refer all B. t. u. determinations to the actual coal basis¹ for the sake of comparison. For this purpose the following formula was used.

$$\frac{\text{B. t. u. as determined} - 5000 \times \text{Weight of Sulphur}}{1.00 - (\text{Moisture} + 1.08 \times \text{Ash} + 22/40 \times \text{Sulphur})}$$

¹Bul. No. 37, Eng. Exp. Sta., 1909. S. W. Parr and W. F. Wheeler.

For the benefit of anyone who has not a copy of Bulletin No. 37 at hand, a brief explanation of some of the terms used in the formula follows:

" $5000 \times \text{Weight of Sulphur}$ " in pounds per pound of coal represents the heating value of the sulphur in B. t. u. This is deducted from the heating value of the coal given by the calorimeter in order to overcome any variation in the amount of sulphur present in the several coal samples. For purposes of comparison, it is found advisable to consider the sulphur as being extraneous matter and not as part of the coal substance. The term " $1.08 \times \text{Ash}$ " represents the mineral matter of the coal that remains after burning completely, and also an additional eight per cent for the water and carbon dioxide that were not part of the coal, but were chemically combined with the mineral matter of the ash and thus took the place of an equal weight of actual coal. The last term " $22/40 \times \text{Sulphur}$ " represents the sulphur corrected for the oxygen that replaces it in the ash. When the coal is burned, any sulphur that was combined with iron as pyrite, FeS_2 , is replaced by oxygen, leaving Fe_2O_3 in ash. This exchange results in a loss in weight of only $5/8$ the amount of sulphur burned. Since part of the sulphur is not combined in the form of pyrites, but is in a form which is non-combustible and may remain in the ash, the fraction $22/40$ is taken instead of $25/40$ as being more nearly the figure which would properly be applied. The denominator, taken as a whole, gives the weight of actual coal in a unit weight of coal as analyzed."

It was found that coal samples, even when kept sealed in glass jars for a few months, change appreciably in calorific value.¹ To avoid any such changes, the analyses and calorimetric determinations were all made not later in any case than ten days after sampling the coal. The Mahler-Atwater bomb calorimeter with platinum lining using compressed oxygen was used for all calorimeter tests. The calorimeter room is shown in Fig. 7.

The change in calorific value of the coal was found to be most rapid during the first few weeks after mining, but it was found to continue at a decreasing rate for more than a year certainly, and probably it continues indefinitely. The greater losses in calorific value occur in the smaller sizes of coal, the screenings in practically every instance suffering more of a loss than the nut coal. The greatest loss in any instance was found in the Sangamon county screenings.

¹Bul. No. 17, Eng. Exp. Sta. S. W. Parr and W. F. Wheeler. J. Am. Chem. Soc., Vol. 30, p. 1027

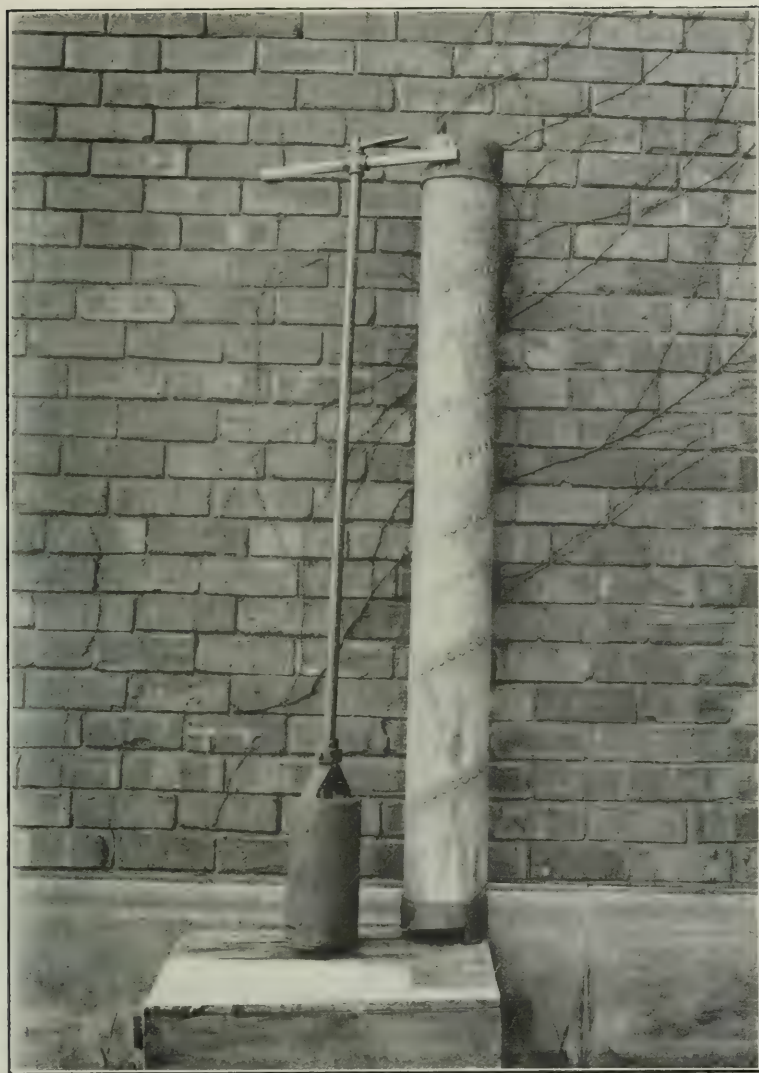


Fig. 6

and that was but 5.14 per cent. The average losses for all sizes and both methods of storage, in open and covered bins, for one year is practically 3 per cent. Tables 6 to 12 inclusive and Fig. 8 to 15 inclusive show the losses for coals from different seams and different storage



Fig. 7

conditions. Table 12 is made up of average values from the six preceding tables, and it seems reasonable to suppose that it shows about what may be expected of Illinois coals when stored. The loss for one year was found to be only 2.76 per cent when exposed to the weather, against 3.14 per cent when in covered bins, and 1.49 per cent when stored under water. Nearly one-third of the loss took place during shipment, except in the case of the coal stored under water, when more than one-half of the loss occurred in the first week. None of the losses in calorific value thus far noted are great enough to warrant any changes in present storage methods, but there is a possibility that protection from spontaneously ignited fires and lessened breakage may make storage under water advisable in many instances.

The Christian county coal heated to a considerable extent and

TABLE 6
VERMILION COUNTY, ILLINOIS, NUT COAL

Lab. No.	Sample Taken	Dry Coal			B. t. u. Referred to Actual or Unit Coal ¹	Decrease	
		Ash	Sulphur	B. t. u.		B. t. u.	per cent
Stored in Exposed Bins							
1031	Same day as mined.....	10.55	4.25	12991	14814	.....	.....
1081	7 days after mining.....	13.98	2.65	12412	14716	98	.66
1240	2 months " ".....	14.21	2.47	12265	14577	237	1.60
1656	6 " " ".....	13.53	2.10	12396	14575	239	1.61
2088	1 year " ".....	13.62	2.82	12282	14498	316	2.13
Stored in Covered Bins							
1031	Same day as mined.....	10.55	4.25	12991	14814	...	....
1081	7 days after mining.....	13.98	2.65	12412	14716	98	.66
1249	2 months " ".....	13.08	2.13	12475	14604	210	1.42
1662	6 " " ".....	11.76	2.14	12571	14472	342	2.31
2094	1 year " ".....	13.52	2.72	12220	14403	411	2.77
Stored under Water							
1031	Same day as mined.....	10.55	4.25	12891	14814	...	....
1081	" " " submerged.....	13.98	2.65	12412	14716	98	.66
1647	6 months after mining.....	15.37	3.34	12013	14524	290	1.96
2100	1 year " ".....	13.85	3.81	12231	14517	297	2.00

¹ For meaning of actual or unit coal, see formula on page 23.

caught fire several times, the fire in each case being extinguished by a large quantity of water. Even in this case the loss was not of a very serious nature, being less than 3 per cent, only a little higher than would have occurred if the coal had not heated at all.

The coal from Fulton county showed a small decrease, only 0.7 per cent, in calorific value, when compared with coal two weeks after mining. If a fresher sample of coal had been available for determining the original B. t. u. value, the loss shown would have been at least double that found. The analyses of the coals from Christian and Fulton counties are found in Table 13.

For some unknown reason, the losses in calorific value shown in Table 14 for the second lot of Vermilion county screenings after about two and one-half years' storage are less than might be expected considering the losses shown by the other coal from the same county.

TABLE 7
WILLIAMSON COUNTY, ILLINOIS, NUT COAL

Lab. No.	Sample Taken	Dry Coal			B. t. u. Referred to Actual or Unit Coal	Decrease		
		Ash	Sulphur	B. t. u.		B. t. u.	per cent	
Stored in Exposed Bins								
1090	Same day as mined.....	13.98	3.73	12499	14859	...	....	
1091								
1098		7 days after mining.....	14.90	3.02	12341	14821	38	.26
1246		2 months " ".....	14.32	4.12	12409	14835	24	.16
1657		6 " " ".....	13.81	3.45	12455	14765	95	.64
2090	1 year " ".....	11.88	2.73	12759	14734	125	.84	
Stored in Covered Bins								
1090	Same day as mined.....	13.98	3.73	12499	14859	...	....	
1091								
1098		7 days after mining.....	14.90	3.02	12341	14821	38	.26
1247		2 months " ".....	14.08	3.84	12378	14739	120	.81
1663		6 months " ".....	13.06	3.60	12469	14644	215	1.45
2096	1 year " ".....	13.24	3.20	12428	14616	243	1.64	
Stored under Water								
1090	Same day as mined.....	13.98	3.73	12499	14859	...	....	
1091								
1098		" " " submerged.....	14.90	3.02	12341	14821	38	.26
1648		6 months after mining.....	15.65	3.12	12097	14673	186	1.25
2102		1 year " ".....	14.87	3.42	12251	14721	138	.93

(See Tables 6 and 9.) The changes for the second year are shown to be only about one-half those for the first year. However, in this case, the coal seems to have reached a stage where the loss occurs at a uniform rate of about 0.1 per cent per month where the coal is stored without protection from the weather.

About fifteen months after mining, one sample was taken from this lot of coal to represent the whole pile and another to represent the outside six inches of the pile, with the expectation that the surface layers would show greater losses than the whole mass. The calorific values of the two samples, however, varied by only a few B. t. u., not a difference greater than the limit of accuracy of the determination.

Coal that will weather in the open air ought to weather to almost

TABLE 8
SANGAMON COUNTY, ILLINOIS, NUT COAL

Lab. No.	Sample Taken	Dry Coal			B. t. u. Referred to Actual or Unit Coal	Decrease	
		Ash	Sulphur	B. t. u.		B. t. u.	per cent
Stored in Exposed Bins							
1078	Same day as mined.....	17.87	5.75	11741	14773	.....	....
1084	7 days after mining.....	16.63	5.10	11800	14571	202	1.37
1248	2 months “ “.....	17.45	4.66	11626	14497	276	1.87
1658	6 “ “ “.....	16.03	4.91	11798	14444	329	2.23
2086	1 year “ “.....	14.97	4.68	11860	14307	466	3.15
Stored in Covered Bins							
1078	Same day as mined.....	17.87	5.75	11741	14773	....	.....
1084	7 days after mining.....	16.63	5.10	11800	14571	202	1.37
1250A	2 months “ “.....	16.08	5.03	11912	14600	173	1.17
1250B	2 “ “ “.....	17.57	5.01	11626	14535	238	1.61
1664	6 “ “ “.....	16.30	4.52	11682	14336	437	2.96
2092	1 year “ “.....	15.99	4.65	11589	14165	608	4.12
Stored under Water							
1078	Same day as mined.....	17.87	5.75	11741	14773	...	....
1084	“ “ “ submerged.....	16.63	5.10	11800	14571	202	1.37
1649	6 months after mining.....	15.90	4.21	11854	14461	322	2.18
2098	1 year “ “.....	15.95	5.11	11851	14503	270	1.83

as great an extent when exposed in the mine, but samples taken from old pillars in two Illinois mines, after an exposure for about twenty-five years, show less than three per cent loss in either case. The coal showed no shrinkage or change in physical appearance in either of these pillars after about one-half inch of dirty coal was removed from the surface. The analyses of these samples of old coal and of a sample from an outcrop in Peoria county are presented in Table 15. This outcrop coal represents the greatest deterioration that has so far come to our knowledge. In fact, the sample from the outcrop shows almost a complete change in the character of the coal. It has every physical appearance of a brown lignite, while the unaltered coal from the same seam was a fair grade of bituminous coal not different from other Illinois coals. This change appears to be in the wrong direction to agree with most of the accepted theories of coal formation. Most of the writers on coal formation think that our coal deposits

TABLE 9
VERMILION COUNTY, ILLINOIS, SCREENINGS

Lab. No.	Sample Taken	Dry Coal			B. t. u. Referred to Actual or Unit Coal	Decrease	
		Ash	Sulphur	B. t. u.		B. t. u.	per cent
Stored in Exposed Bins							
1032	Same day as mined.....	17.88	2.35	11937	14888	...	....
1080	7 days after mining.....	13.98	2.87	12414	14726	162	1.09
1082	7 " " ".....	13.69	2.29	12507	14759	129	.87
1238	2 months " ".....	15.73	2.53	11958	14497	391	2.63
1239	2 " " ".....	14.69	2.90	12178	14578	310	2.08
1653	6 " " ".....	15.63	2.44	11969	14487	401	2.69
2089	1 year " ".....	14.46	2.24	12006	14304	584	3.92
Stored in Covered Bins							
1032	Same day as mined.....	17.88	2.35	11937	14888	...	....
1080	7 days after mining.....	13.98	2.87	12414	14726	162	1.09
1082	7 " " ".....	13.69	2.29	12507	14759	129	.87
1241	2 months " ".....	15.26	2.51	12124	14608	280	1.88
1659	6 " " ".....	14.51	2.25	12071	14391	497	3.34
2095	1 year " ".....	15.36	2.42	11797	14225	663	4.46
Stored under Water							
1032	Same day as mined.....	17.88	2.35	11937	14888	...	....
1080	" " " submerged.....	13.98	2.87	12414	14726	162	1.09
1082	" " " ".....	13.69	2.29	12507	14759	129	1.87
1644	6 months after mining.....	13.87	2.32	12270	14514	374	2.51
2101	1 year " ".....	13.55	2.71	12283	14483	405	2.72

have gone through the various stages from peat to anthracite. In this case the sulphur is almost free from the coal, supposedly by oxidation and leaching. The thickness of the No. 5 coal seam is remarkably uniform in this locality, and the thickness of the outcrop coal is not different from the thickness of the seam in other places near-by where the coal is unchanged. Thus, no evidence is offered that the seam at this place had suffered any very great shrinkage.

The coal stored by the Commonwealth Edison Company of Chicago was sampled after fifteen months' storage and losses of only about one per cent were found, although the final samples were taken from the surface of the piles. (See analytical results, Table 16.) The

TABLE 10
WILLIAMSON COUNTY, ILLINOIS, SCREENINGS

Lab. No.	Sample Taken	Dry Coal			B. t. u. Referred to Actual or Unit Coal	Decrease	
		Ash	Sulphur	B. t. u.		B. t. u.	per cent
Stored in Exposed Bins							
1089	Same day as mined.....	14.13	3.17	12426	14782	...	....
1099	7 days after mining.....	14.37	3.34	12287	14666	116	.78
1244	2 months " ".....	15.66	2.67	12133	14701	81	.55
1654	6 " " ".....	13.76	2.84	12342	14597	185	1.25
2091	1 year " ".....	13.77	2.75	12328	14579	203	1.37
Stored in Covered Bins							
1089	Same day as mined.....	14.13	3.17	12426	14782	...	....
1099	7 days after mining.....	14.37	3.34	12287	14666	116	.78
1245	2 months " ".....	12.62	2.98	12608	14705	77	.52
1660	6 " " ".....	13.60	3.03	12372	14610	172	1.16
2097	1 year " ".....	13.43	2.72	12385	14582	200	1.35
Stored under Water							
1089	Same day as mined.....	14.13	3.17	12426	14782	...	....
1099	" " " submerged.....	14.37	3.34	12287	14666	116	.78
1645	6 months after mining.....	14.38	3.54	12262	14645	137	.93
2103	1 year " ".....	13.60	2.97	12447	14698	84	.57

coal in these large piles seemed to have broken up very slightly, and no objectionable heating was noticed.

VII. CONCLUSIONS

Coal of the type found in Illinois and neighboring states is not affected seriously during storage when only the changes in weight and losses in heating power are considered. The changes in weight may be either gains or losses of probably never over two per cent in a period of one year. The heating value decreases most rapidly during the first week after mining and continues to decrease more and more slowly for an indefinite time. In the coals that have been tested, one per cent is about the average loss for the first week and three to three and one-half per cent would cover the losses for a year,

TABLE 11
SANGAMON COUNTY, ILLINOIS, SCREENINGS

Lab. No.	Sample Taken	Dry Coal			B. t. u. Referred to Actual or Unit Coal	Decrease	
		Ash	Sulphur	B. t. u.		B. t. u.	per cent
Stored in Exposed Bins							
1079	Same day as mined. .	17.13	4.92	11752	14604	...	....
1085	7 days after mining.	17.04	4.47	11684	14481	123	.84
1242	2 months " "	17.22	5.00	11645	14488	116	.79
1655	6 " " "	17.02	4.54	11526	14281	323	2.21
2087	1 year " "	17.25	4.54	11153	13853	751	5.14
Stored in Covered Bins							
1079	Same day as mined. .	17.13	4.92	11752	14604	...	....
1085	7 days after mining. .	17.04	4.47	11684	14481	123	.84
1243	2 months " " "	18.33	4.70	11414	14404	200	1.37
1661	6 " " "	17.30	4.67	11466	14263	341	2.33
2093	1 year " " "	17.06	4.73	11248	13944	660	4.52
Stored under Water							
1079	Same day as mined.	17.13	4.92	11752	14604	...	....
1085	" " " submerged. .	17.04	4.47	11684	14481	123	.84
1646	6 months after mining. .	19.86	5.60	11127	14372	232	1.59
2099	1 year " " " "	18.27	4.81	11479	14478	126	.86

although in some instances the loss was found to be as high as five per cent in a year.

The losses due to disintegration of the coal and to spontaneous ignition seem to be of far greater importance than any changes in weight and heating value, although they cannot be expressed in figures for comparison. The storage of coal of a size larger than is to be used would overcome part of this objection to storage, as the coal could be crushed to the most advantageous size just before firing. The larger sizes of coal are also much less liable to take fire spontaneously. Storage under water will prevent disintegration of the coal to a very large extent, and it will absolutely prevent any fire losses. Aside from these advantages in favor of storing coal under water, there seems to be very little to be said in favor of any particular method of storing coal.

TABLE 12

AVERAGE VALUES FROM SIX PRECEDING TABLES

Sample Taken	Dry Coal			B. t. u. Referred to Actual or Unit Coal ¹	Decrease		
	Ash	Sulphur	B. t. u.		B. t. u.	per cent	
Stored in Exposed Bins							
Same day as mined.	15.26	4.03	12224	14787	...	...	
7 days after mining.	15.13	3.53	12164	14666	121	.82	
2 months " "	15.68	3.61	12024	14606	181	1.22	
6 " " "	14.96	3.36	12081	14525	262	1.77	
1 year " "	14.33	3.29	12065	14379	408	2.76	
Stored in Covered Bins							
Same day as mined.	15.26	4.03	12224	14787	...	...	
7 days after mining.	15.13	3.53	12164	14666	121	.82	
2 months " "	15.07	3.53	12128	14605	182	1.22	
6 " " "	14.42	3.37	12105	14453	334	2.26	
1 year " "	14.77	3.57	11945	14323	464	3.14	
Stored under Water							
Same day as mined.	15.26	4.03	12224	14787	...	...	
" " " submerged.	15.13	3.53	12164	14666	121	.82	
6 months after mining.	15.84	3.69	11937	14532	255	1.73	
1 year " "	15.02	3.81	12090	14567	220	1.49	

TABLE 13

CHRISTIAN COUNTY, ILLINOIS, SCREENINGS

Lab. No.	Sample Taken	Dry Coal			B. t. u. Referred to Actual or Unit Coal	Decrease	
		Ash	Sulphur	B. t. u.		B. t. u.	per cent
1422	When stored (about 2 weeks after mining)	19.20	5.04	11325	14475	...	...
	Five months in exposed pile of 500 tons (had heated badly)	16.68	4.43	11425	14083	392	2.71
FULTON COUNTY, ILLINOIS, SCREENINGS.							
1405	Two weeks after mining . . .	20.97	3.42	11114	14500	...	...
1406	Six months in exposed pile three feet deep	21.12	3.17	11021	14398	1.02	70

¹ For meaning of actual or unit coal, see formula on page 23.

TABLE 14
VERMILION COUNTY, ILLINOIS, SCREENINGS

Lab. No.	Sample Taken	Dry Coal			B. t. u. Referred to Actual or Unit Coal ¹	Decrease	
		Ash	Sulphur	B. t. u.		B. t. u.	per cent
In Exposed Pile							
.....	When mined.....	.....	.....	.....	14850 ²	...	.....
144	About two weeks after min-						
147	ing.....	19.11	1.96	11561	14644	206	1.39
973	15 months after mining.....	19.54	2.20	11368	14491	359	.42
1627	22 " " " ".....	20.61	1.88	11134	14392	458	3.08
2104	28 " " " ".....	21.70	1.83	10901	14307	543	3.66
Stored under Water							
.....	When mined.....	.....	.....	.....	14850	...	.....
975	15 months after submerging.	15.90	2.29	12154	14761	89	.60
2105 ³	28 " " " ".....	17.75	1.97	11686	14531	319	2.15

¹ Calorific value taken from other analyses of fresh coal from same mine and neighboring mines.

² Coal was not completely covered with water for last two months.

³ For meaning of actual or unit coal, see formula on page 23.

TABLE 15
ANALYSES OF PILLAR-COAL AND OUTCROP COAL COMPARED WITH FRESH COAL

Lab. No.	Description	Total Moisture	Dry Coal			B. t. u. Referred to Actual or Unit Coal	Decrease	
			Ash	Sulphur	B. t. u.		B. t. u.	per cent
ST. CLAIR COUNTY, ILLINOIS								
991	Fresh Coal.	9.76	15.80	4.76	12202	14896	...	....
992	Pi lar-coal exposed 22 years.	10.18	16.21	5.01	11797	14482	414	2.78
GALLATIN COUNTY, ILLINOIS								
1092	Fresh coal.	4.47	10.85	3.72	13235	15133	...	....
1093	Pillar-coal exposed 27 years.	4.76	13.84	3.84	12514	14857	276	1.82
PEORIA COUNTY, ILLINOIS								
1407	Fresh coal.	13.86	16.25	3.91	12044	14757	...	....
1402	Outerop coal, slight- ly covered with soil.	29.81	16.86	.85	9257	11331	3426	23.21

TABLE 16
COMMONWEALTH EDISON COMPANY, CHICAGO
Stored Coal

Lab. No.	Sample Taken	Dry Coal			B. t. u. Referred to Actual or Unit Coal ¹	Decrease	
		Ash	Sulphur	B. t. u.		B. t. u	per cent
FRANKLIN CO., ILLINOIS							
Nut Coal							
1337	April, 1908.	10.16	1.81	13021	14688	....	....
1414							
2619	July 14, 1909.	10.44	2.15	12924	14642	46	.31
WILLIAMSON COUNTY AND FRANKLIN COUNTY, ILLINOIS							
Egg Coal							
1335	April, 1908.	10.97	2.35	12909	14728	...	....
1415							
2620	July 14, 1909.	11.49	1.84	12697	14559	169	1.15
WILLIAMSON CO., ILLINOIS							
No. 1 Washed Nut							
1336	April, 1908.	9.21	1.82	13205	14726	...	....
1416							
2618	July 14, 1909.	9.43	1.72	13008	14540	186	1.26

¹ For meaning of actual or unit coal, see formula, p. 23.

VERMILION COUNTY, ILLINOIS

NUT COAL

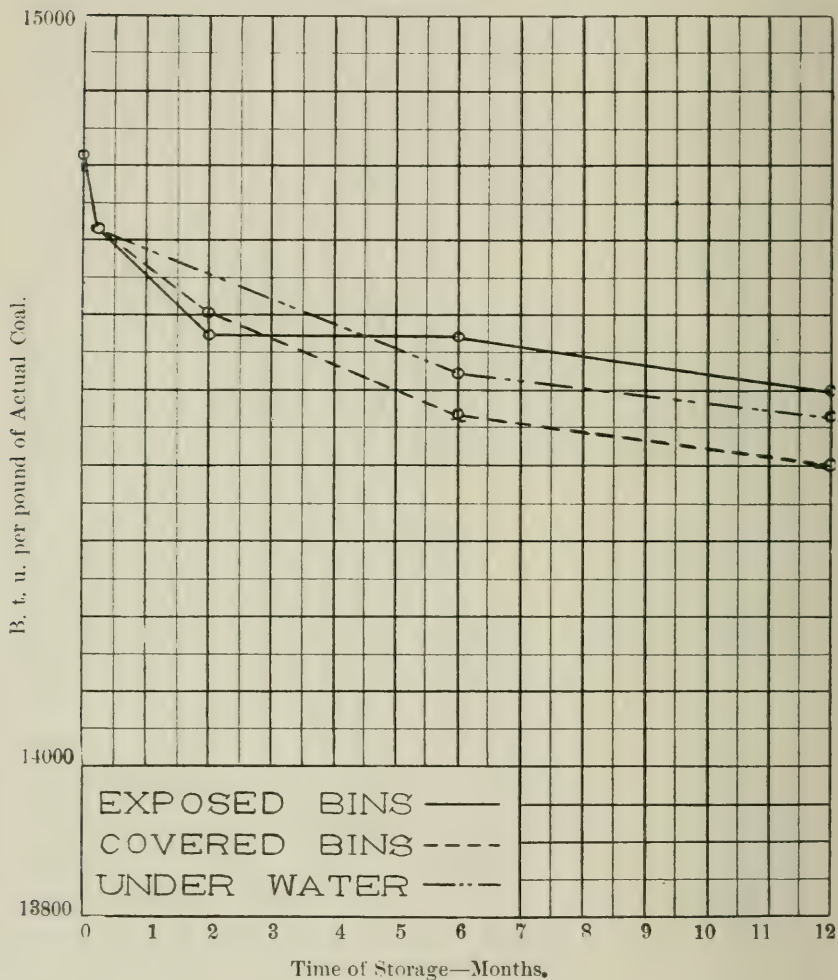


Fig. 8

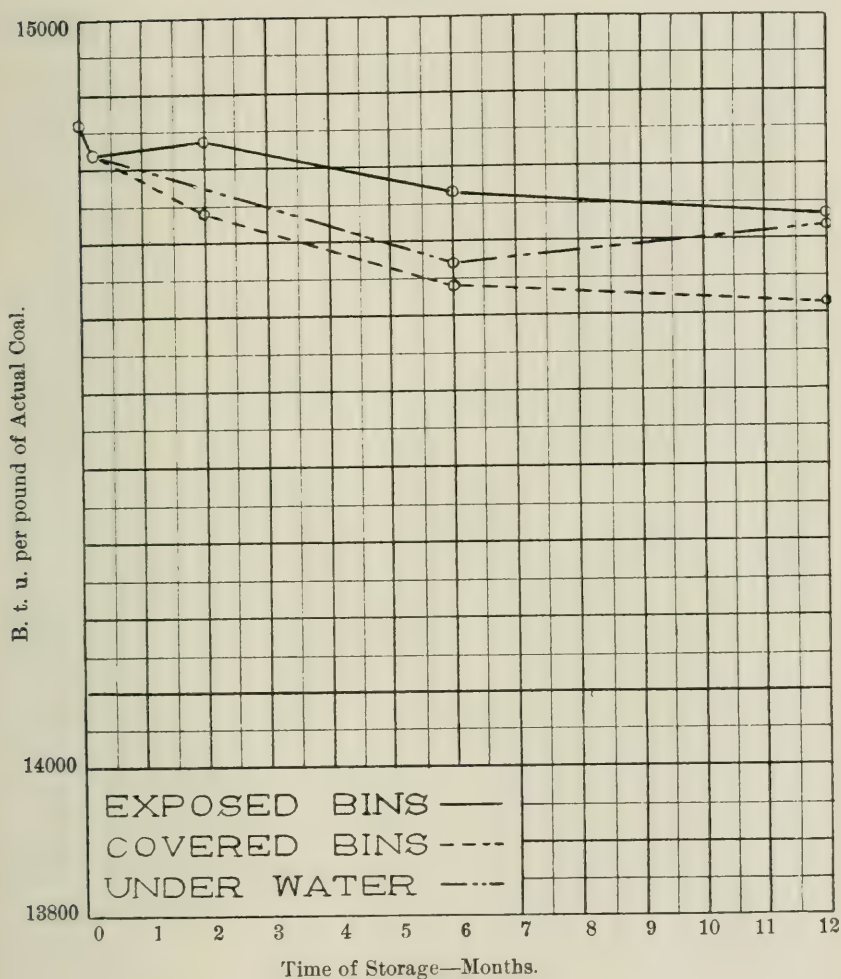
WILLIAMSON COUNTY, ILLINOIS
NUT COAL

Fig. 9

SANGAMON COUNTY, ILLINOIS

NUT COAL

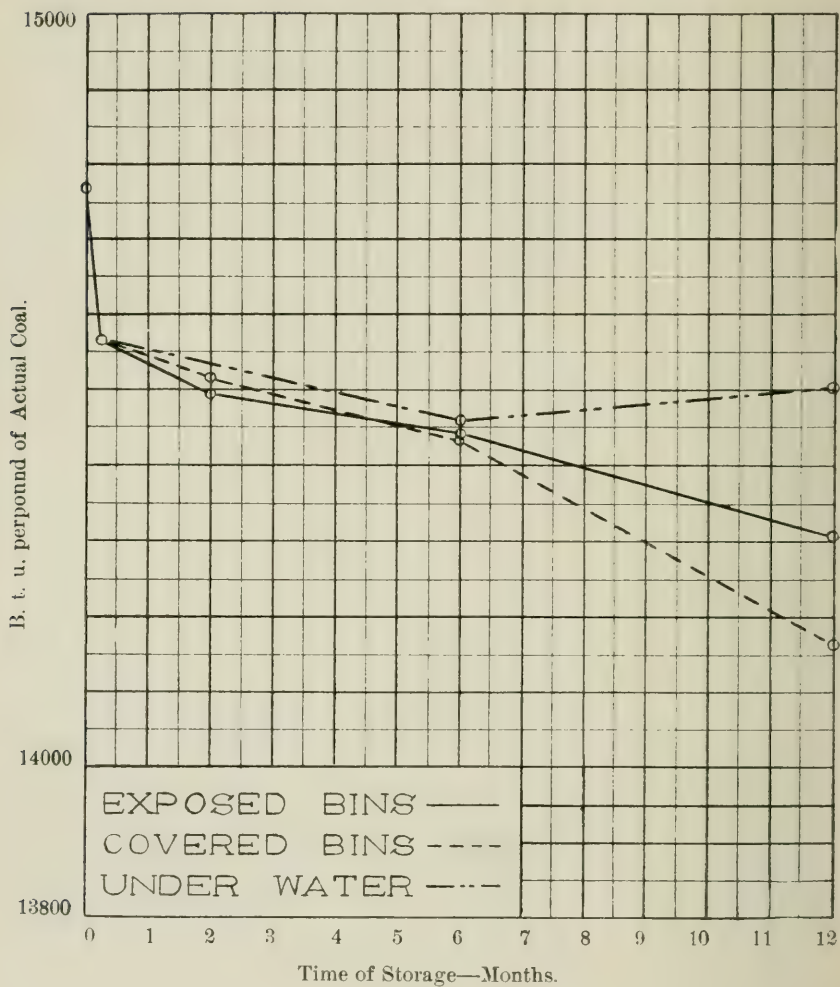


Fig. 10

VERMILION COUNTY, ILLINOIS

SCREENINGS

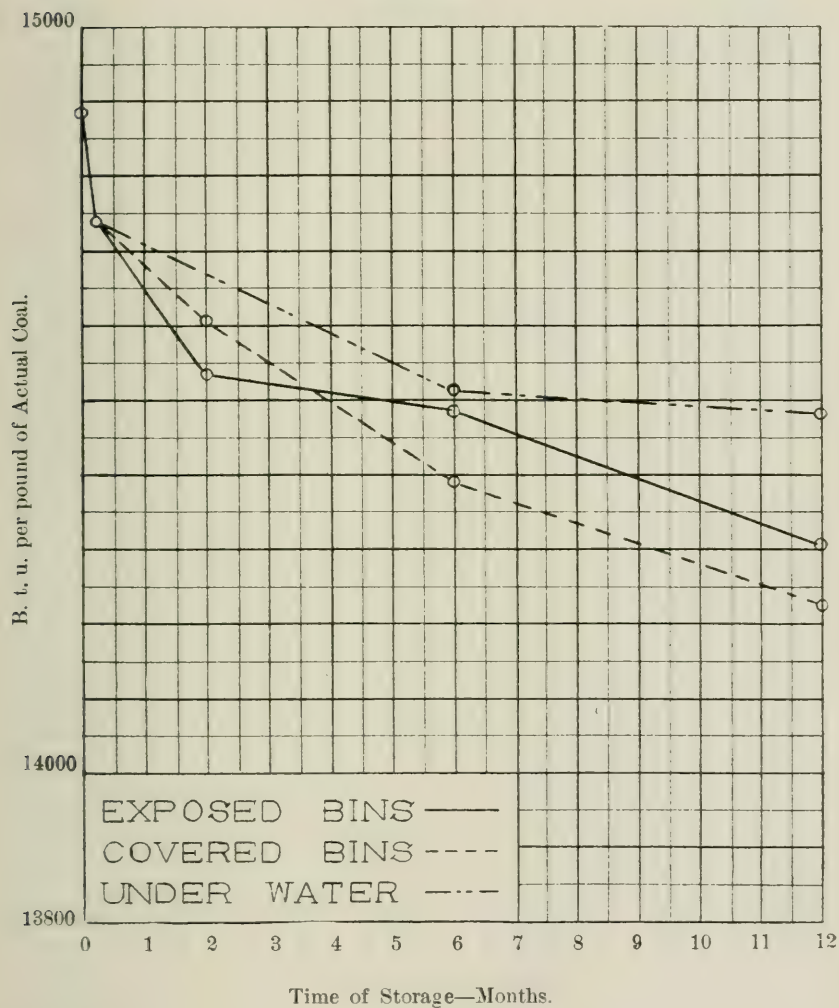


Fig. 11

VERMILION COUNTY, ILLINOIS

SCREENINGS

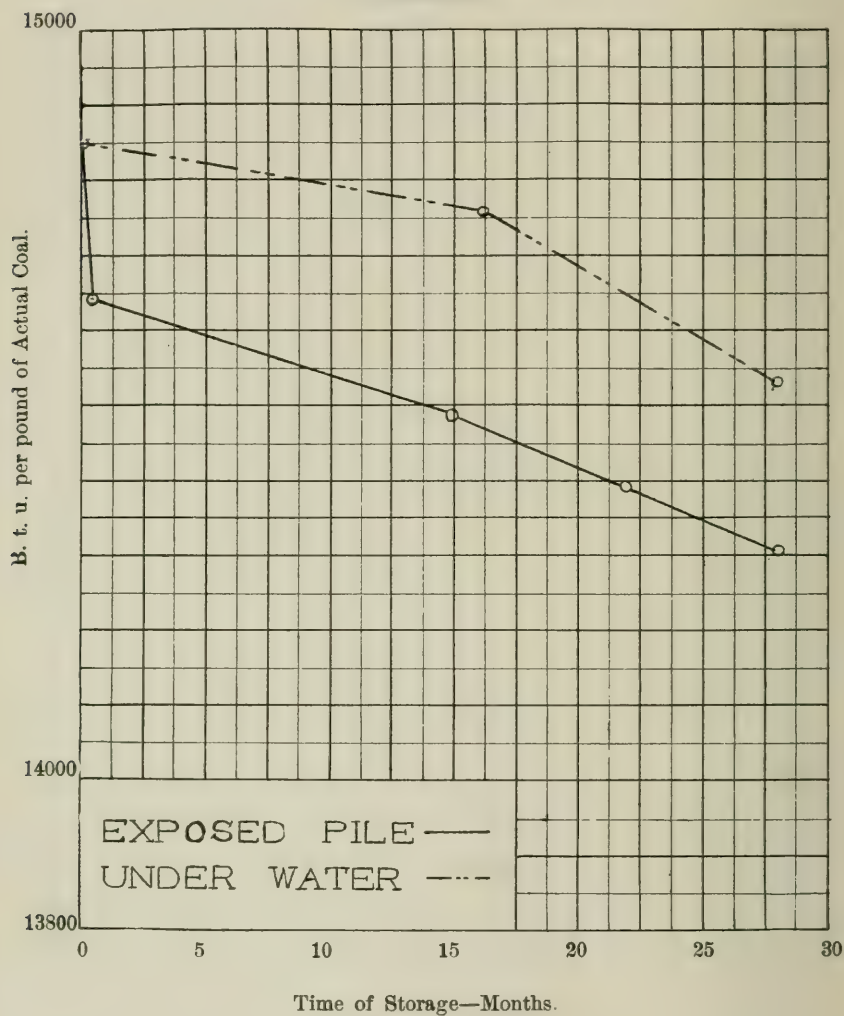


Fig. 12

WILLIAMSON COUNTY, ILLINOIS

SCREENINGS

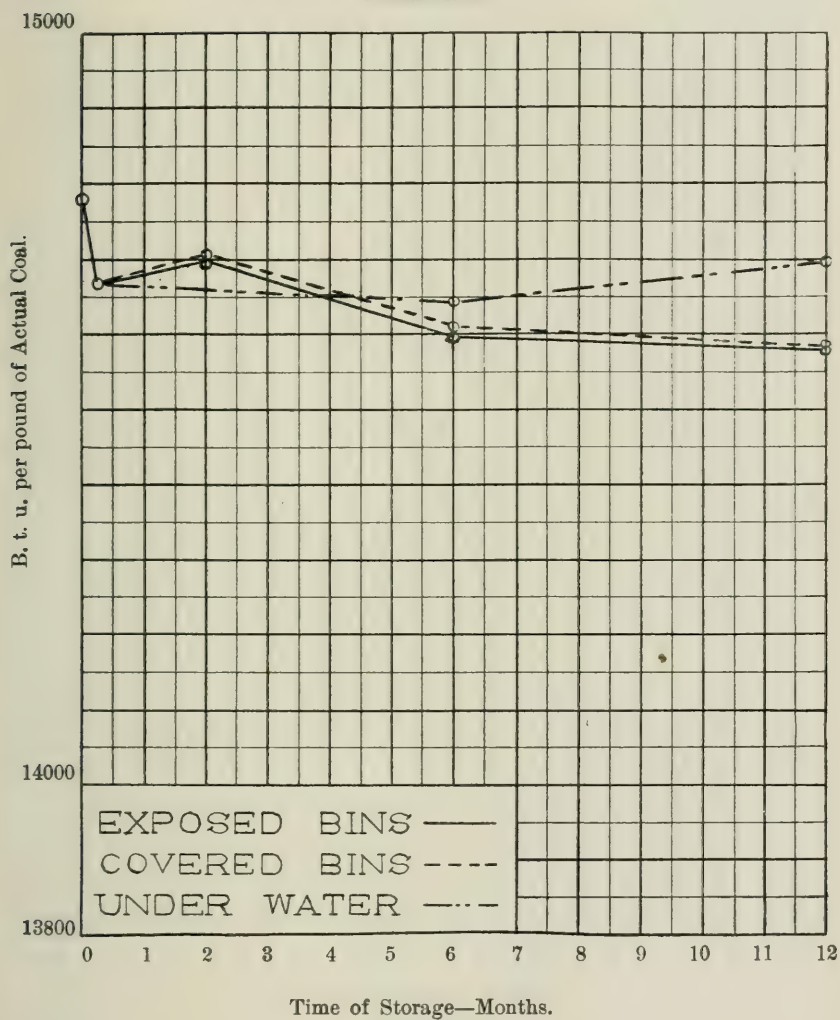


Fig. 13

SANGAMON COUNTY, ILLINOIS

SCREENINGS

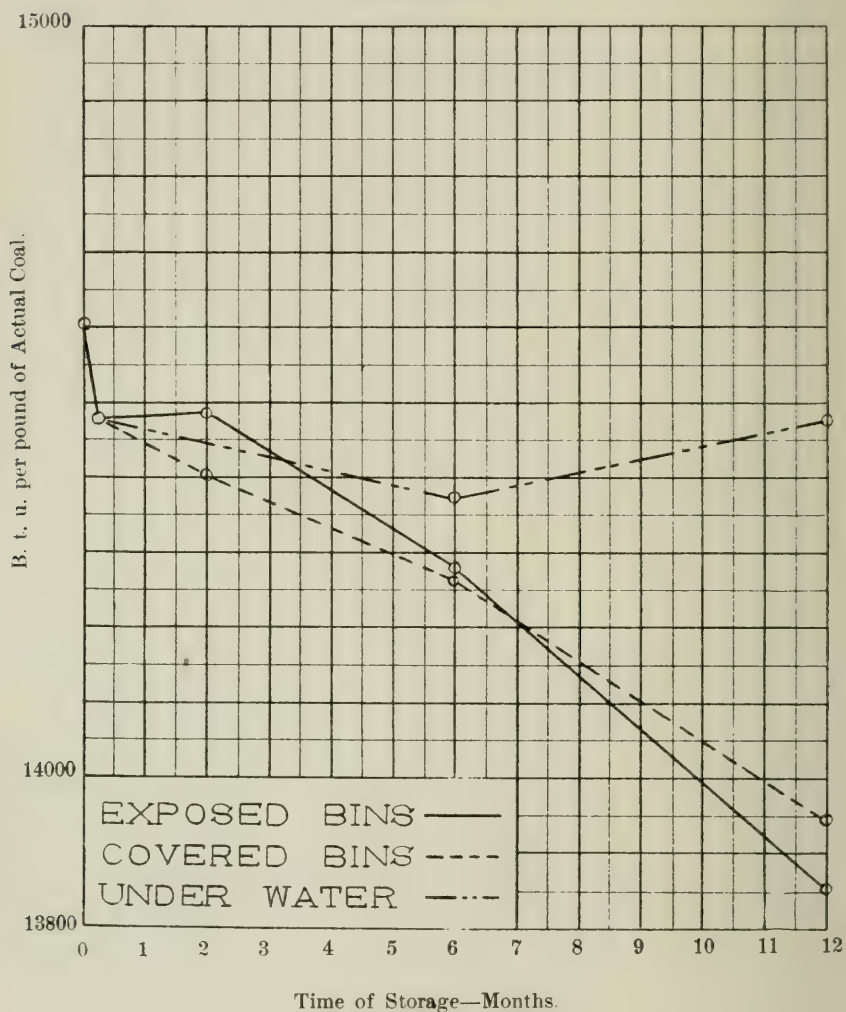


Fig. 14

AVERAGE VALUES FROM THE SIX PRECEDING TABLES.

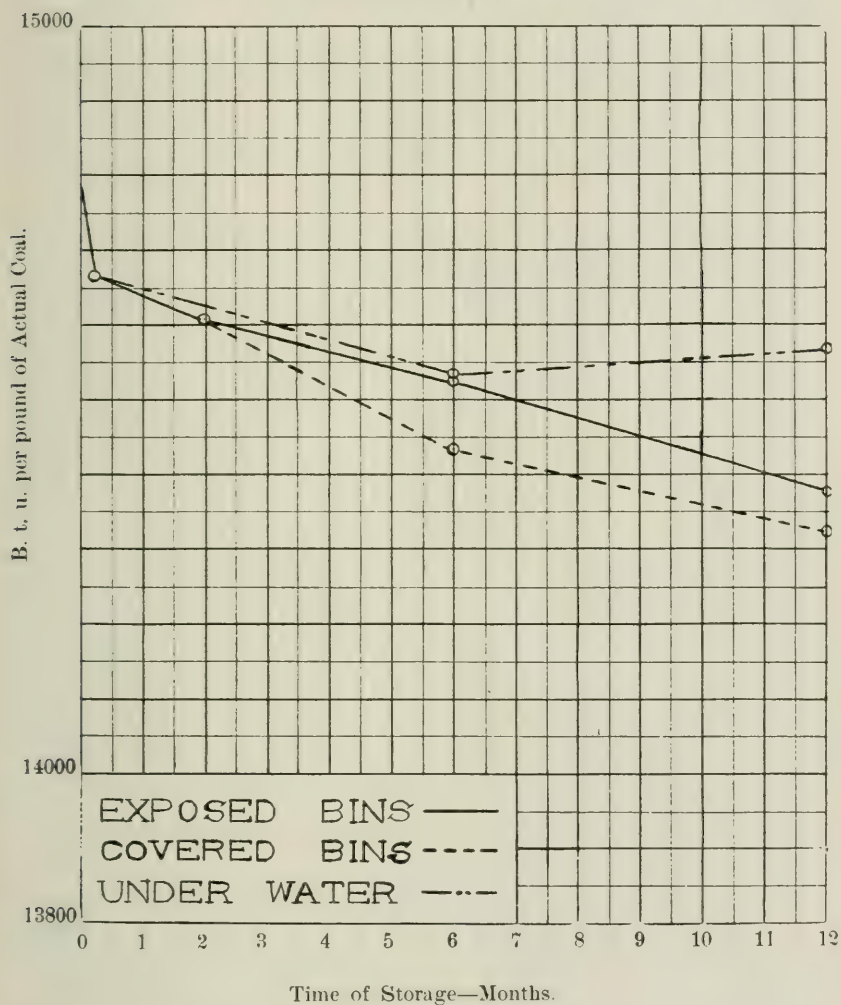


Fig. 15

PUBLICATIONS OF THE ENGINEERING EXPERIMENT STATION

- Bulletin No. 1.* Tests of Reinforced Concrete Beams, by Arthur N. Talbot. 1904. (Out of print.)
- Circular No. 1.* High-Speed Tool Steels, by L. P. Breckenridge. 1905. (Out of print.)
- Bulletin No. 2.* Tests of High-Speed Tool Steels on Cast Iron, by L. P. Breckenridge and Henry B. Dirks. 1905. (Out of print.)
- Circular No. 2.* Drainage of Earth Roads, by Ira O. Baker. 1906. (Out of print.)
- Circular No. 3.* Fuel Tests with Illinois Coal. (Compiled from tests made by the Technologic Branch of the U. S. G. S., at the St. Louis, Mo., Fuel Testing Plant, 1904-1907, by L. P. Breckenridge and Paul Diserens. 1909.
- Bulletin No. 3.* The Engineering Experiment Station of the University of Illinois, by L. P. Breckenridge. 1906. (Out of print.)
- Bulletin No. 4.* Tests of Reinforced Concrete Beams. Series of 1905, by Arthur N. Talbot. 1906.
- Bulletin No. 5.* Resistance of Tubes to Collapse, by Albert P. Carman. 1906. (Out of print.)
- Bulletin No. 6.* Holding Power of Railroad Spikes, by Roy I. Webber. 1906. (Out of print.)
- Bulletin No. 7.* Fuel Tests with Illinois Coals, by L. P. Breckenridge, S. W. Parr and Henry B. Dirks. 1906. (Out of print.)
- Bulletin No. 8.* Tests of Concrete: I. Shear; II. Bond, by Arthur N. Talbot. 1906. (Out of print.)
- Bulletin No. 9.* An Extension of the Dewey Decimal System of Classification Applied to the Engineering Industries, by L. P. Breckenridge and G. A. Goodenough. 1906.
- Bulletin No. 10.* Tests of Concrete and Reinforced Concrete Columns, Series of 1906, by Arthur N. Talbot. 1907. (Out of print.)
- Bulletin No. 11.* The Effect of Scale on the Transmission of Heat through Locomotive Boiler Tubes, by Edward C. Schmidt and John M. Snodgrass. 1907. (Out of print.)
- Bulletin No. 12.* Tests of Reinforced Concrete T-beams, Series of 1906, by Arthur N. Talbot. 1907. (Out of print.)
- Bulletin No. 13.* An Extension of the Dewey Decimal System of Classification Applied to Architecture and Building, by N. Clifford Ricker. 1907.
- Bulletin No. 14.* Tests of Reinforced Concrete Beams, Series of 1906, by Arthur N. Talbot. 1907. (Out of print.)
- Bulletin No. 15.* How to Burn Illinois Coal without Smoke, by L. P. Breckenridge. 1908.
- Bulletin No. 16.* A Study of Roof Trusses, by N. Clifford Ricker. 1908.
- Bulletin No. 17.* The Weathering of Coal, by S. W. Parr, N. D. Hamilton, and W. F. Wheeler. 1908. (Out of print.)
- Bulletin No. 18.* The Strength of Chain Links, by G. A. Goodenough and L. E. Moore. 1908.
- Bulletin No. 19.* Comparative Tests of Carbon, Metallized Carbon and Tantalum Filament Lamps, by T. H. Amrine. 1908.
- Bulletin No. 20.* Tests of Concrete and Reinforced Concrete Columns, Series of 1907, by Arthur N. Talbot. 1908.
- Bulletin No. 21.* Tests of a Liquid Air Plant, by C. S. Hudson and C. M. Garland. 1908.
- Bulletin No. 22.* Tests of Cast-Iron and Reinforced Concrete Culvert Pipe, by Arthur N. Talbot. 1908.
- Bulletin No. 23.* Voids, Settlement and Weight of Crushed Stone, by Ira O. Baker. 1908.
- Bulletin No. 24.* The Modification of Illinois Coal by Low Temperature Distillation, by S. W. Parr and C. K. Francis. 1908.
- Bulletin No. 25.* Lighting Country Homes by Private Electric Plants, by T. H. Amrine. 1908.
- Bulletin No. 26.* High Steam-Pressures in Locomotive Service. A Review of a Report to the Carnegie Institution of Washington. By W. F. M. Goss. 1908.
- Bulletin No. 27.* Tests of Brick Columns and Terra Cotta Block Columns, by Arthur N. Talbot and Duff A. Abrams. 1909.
- Bulletin No. 28.* A Test of Three Large Reinforced Concrete Beams, by Arthur N. Talbot. 1909.
- Bulletin No. 29.* Tests of Reinforced Concrete Beams: Resistance to Web Stresses, by Arthur N. Talbot. 1909.
- Bulletin No. 30.* On the Rate of Formation of Carbon Monoxide in Gas Producers, by J. K. Clement, L. H. Adams, and C. N. Haskins. 1909.
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TESTS OF WASHED GRADES OF ILLINOIS COAL

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EXPERIMENT STATION, IN CHARGE OF FUEL TESTS

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A NOTE OF ACKNOWLEDGMENT

A few years ago, Professor L. P. Breckenridge, while Director of the Engineering Experiment Station, outlined an elaborate series of fuel tests to be undertaken by the Station. In the development of his plans, he invited the cooperation of several distinguished engineers, and to them special acknowledgment is made for many helpful suggestions and criticisms. Those who contributed to the work constituted a Fuel Test Conference Committee, the members of which were Messrs. W. L. Abbott, representing the Board of Trustees, University of Illinois; H. Foster Bain, representing the State Geological Survey; A. Bement, representing the Western Society of Engineers; E. H. Cheney, representing the Building Managers' Association of Chicago; F. H. Clark, representing the Western Railway Club; A. Mueller, representing the Illinois Manufacturers' Association; Carl Scholz, representing the Illinois Coal Operators' Association; and A. V. Schroeder, representing the State Electric Light Association. Dr. Bain also gave attention to the selection of the various samples of coal tested. The necessary chemical work was carried on under the direction of Professor S. W. Parr. Material assistance was also rendered by the Technologic Branch of the United States Geological Survey, as represented by its chief, Mr. J. A. Holmes. The author, Mr. C. S. McGovney, acting under the general direction of Professor Breckenridge, has been responsible for the immediate charge and direct supervision of the work.

The work of testing, which proceeded under these plans, has been advanced by methods involving the utmost care, and with results, which, in part, are presented by this bulletin. While the present publication is complete in the sense that it constitutes a final presentation of data covering a definite field, it is to be accepted as a report of a particular phase of the work, rather than as a complete definition of the plans of the Fuel Test Committee.

W. F. M. G.

Engineering Experiment Station
University of Illinois
February, 1910

I. INTRODUCTION

1. During the years 1906 and 1907, the Engineering Experiment Station conducted a series of steam boiler trials as part of an investigation of the fuel value of certain Illinois coals. The results of these tests and a discussion of their significance will be found in the following pages. The data apply specifically to a Heine 210 horse-power water-tube boiler, set singly, and served with a 54-in. Green traveling link grate operated under induced draft pressure. A description of this plant will be found in Appendix I.

2. *Object of the Tests.*—This study has for its primary object the comparison of various grades of Illinois washed coal. With this in view, the tests were planned to facilitate comparisons with respect to the following points:

(a) Determination of the relation of grade of coal to the economy of evaporation and horse-power obtainable.

(b) Determination of the effect of varying rates of combustion upon the economy with various grades.

(c) Effect of different depths of fuel beds.

(d) Study of the fuel bed, draft and draft pressure requirements for each grade.

3. *Development of Methods.*—In experimental furnace work, the difficulty of controlling variables and measuring quantities depends in some degree upon the peculiarities of the furnace and the object of the experimental work. In the present work it has been the aim to pursue such methods and to keep such records of furnace events as will permit comparisons with future experimental work with the particular plant used. Details of these methods and records have been described at proper places in the report and care has been taken to point out irregularities that have occurred. Those methods toward which special study has been directed and which are perhaps of interest aside from their bearing upon the general results contained herein are:

(a) Method of sampling flue gases, see page 88.

(b) System for recording furnace observations and the details of furnace control in fuel tests with the chain grate stoker, see page 92.

II. THE COAL USED

4. *The Coal* used was selected wholly on account of the sizes represented and not for the purpose of comparing coals from various seams or mines in the State. Direct transportation facilities also influenced the selection because of limited storage capacity at the University.

Coal from washing plants in two districts was selected. That from Vermilion county is believed to be characteristic of the washed coal from the seam mined. Coal from this locality has been widely known as "Grape Creek" coal. The coal from Williamson county, including both washed and unwashed coal, is representative of the coal mined from Seam No. 7 in that and adjoining counties.

The stratigraphy of the seam mined in Vermilion county has been questioned for various technical reasons. The same seam characteristics as are found in Seam No. 7 mined in Williamson, Franklin and Jackson counties are, however, present, although the chemical properties of coals from the two seams show sharp differentiations.

5. *The Washing* plants now in operation in the State number about forty. With few exceptions round-hole revolving screens are used, but the size of coal prepared by these varies. By agreement, in 1903, the operators in Williamson county adopted the following standard of sizes for washed coal. The numbers used refer to screens with round perforations.

Designa- tion	Through	Over
No. 1	3 in.	1 $\frac{3}{4}$ in.
No. 2	1 $\frac{3}{4}$ in.	1 in.
No. 3	1 in.	$\frac{3}{4}$ in.
No. 4	$\frac{3}{4}$ in.	$\frac{1}{4}$ in.
No. 5	$\frac{1}{4}$ in.	.....

This gradation has been, in the main, adopted, although several of the mines in that county are also supplying intermediate sizes to meet special market demands. Of the total number of washeries in the State, fifteen are supplying these sizes. Other grades of washed coal prepared by one or more plants are between screens of the following perforations:

Perforations inches						Screens
2	1	1 $\frac{1}{2}$	0	....	....	Round hole
1 $\frac{1}{4}$	3 $\frac{1}{4}$	0	...	...	....	Round hole
3	1 $\frac{1}{2}$	3 $\frac{1}{8}$	...	0	....	Round hole
3	1 $\frac{1}{4}$	3 $\frac{1}{4}$	0	....	....	Square hole
3	1 $\frac{3}{4}$	1 $\frac{1}{4}$	1 $\frac{1}{4}$	0	....	Round hole
2 $\frac{1}{8}$	1 $\frac{1}{2}$	1 $\frac{1}{4}$	...	....	....	Round hole. Size below $\frac{1}{4}$ discarded.
1 $\frac{1}{4}$	0	...	...	...	....	Washed screenings
3	1 $\frac{3}{4}$	1	1 $\frac{1}{2}$	1 $\frac{1}{4}$	0	Round hole
3	1 $\frac{3}{4}$	1	3 $\frac{1}{4}$	5-16	$\frac{1}{8}$	Round hole
3	1 $\frac{3}{4}$	1	3 $\frac{1}{4}$	5-16	0	Round hole
1 $\frac{1}{4}$	3 $\frac{1}{4}$	0	...	....	....	Bar screen

6. The tables given below show the character and grade of the coal selected for the experiments.

Table 1 gives the size and description of the coal. The screens in use at each of the mines are rotary screens with round perforations. The fuel symbol, column 2, in this and the tables following, is a convenient index number, adopted to facilitate the keeping of records at the testing plant. The integral number is the mine index while the remainder of the symbol refers to the size and condition of the coal. For example in the number 4.0703, 4 is the mine number. The remainder of the number gives the

TABLE 1 DESCRIPTION OF COAL

No.	Fuel Symbol	Commercial Name	Size of Screen	Condition	Kind of Washer	Location of Mine		Coal Seam
						Town	County	
1	2	3	4	5	6	7	8	9
1	4.0703 W	Washed Pea.	3 $\frac{1}{8}$ -3 $\frac{3}{8}$	Washed	New Century	Westville	Vermilion	6
2	4.0703 W			..	..	..	..	6
3	4.0700 W	W. Pea & Duff	7 $\frac{1}{8}$ 0	..	..	..	..	6
4	4.0300 W	Washed Duff.	3 $\frac{1}{8}$ -0	..	..	..	..	6
5	5.1610 W	No. 2 washed	1 $\frac{3}{4}$ -1	..	Stewart	Herrin	Williamson	7
6	5.1006 W	No. 3 ..	1-3 $\frac{1}{4}$	..	..	..	..	7
7	5.0202 W	No. 4 ..	3 $\frac{1}{4}$ -1 $\frac{1}{4}$	..	..	..	..	7
8	5.0200 W	No. 5 ..	1 $\frac{1}{4}$ -0	..	..	..	..	7
9	6.0403 W	No. 4 ..	1 $\frac{1}{2}$ -1 $\frac{1}{4}$	..	Stewart	Marion	..	7
10	6.0200 W	No. 5 ..	1 $\frac{1}{4}$ 0	..	..	..	..	7
11	7.1610—	No. 2 Nut....	1 $\frac{3}{4}$ 1	Unwashed	.....	Herrin	..	7

size of the screens used in preparing the coal. The number is given in the octonal system, e. g., 1.6 to 1.0, written for convenience .1610, indicates that the size is between $1\frac{6}{8}$ in. and 1 in.; .0703 indicates that the size is between $\frac{7}{8}$ in. and $\frac{3}{4}$ in.; .1006 that the size is between 1 in. and $\frac{6}{8}$ in., etc. Suffixed to these numbers W indicates washed coal and the dash —, unwashed coal. In Table 1, columns 4, 5, 7 and 8 define the meaning of the fuel symbols for every coal tested.

Table 2 gives the results of analyses of composite samples made up from the samples taken during the progress of the tests. The method of preparing these composite samples is explained on page 119. Sampling at the mine in view of the nature of the experiments was not considered necessary. None of the coal was stored for a greater period than six weeks after receipt so that except for changes in moisture content the analyses of the compos-

TABLE 2 AVERAGE COMPOSITION AND CALORIFIC VALUE
OF THE COAL AS FIRED

Analyses of Composite Samples														
No.	Coal Symbol	Chem. Lab. No.	Moisture on Air Drying	Coal as Fired										Calorific Value per pound
				Proximate Analyses										
				Fixed Carbon	Volatile Matter	Ultimate Analyses						Sulphur		
						Total Moisture	Ash	Carbon	Hydrogen	Oxygen	Nitrogen			
1	2	3	4	32.2	33.2	34.2	35.2	37.2	38.2	39.2	40.2	41.2		
			%	%	%	%	%	%	%	%	%	%	B.t.u.	
1	4.0703W	608	14.46	41.45	32.10	18.97	7.48	58.72	3.90	8.36	0.98	1.59	10385	
2	4.0703W	253	13.10	41.35	32.36	18.03	8.26	59.28	3.82	7.85	1.00	1.76	10534	
3	4.0700W	302	14.55	39.30	32.90	18.78	9.02	57.22	3.75	8.55	0.98	1.70	10381	
4	4.0300W	600	17.43	36.49	28.73	22.00	12.78	52.05	3.42	6.60	1.11	2.04	9154	
5	5.1610W	502	6.04	50.44	31.72	9.66	8.24	66.62	4.53	8.57	1.17	1.27	11843	
6	5.1006W	571	4.74	51.18	30.76	9.27	8.79	66.49	4.19	8.86	1.24	1.16	11795	
7	5.0602W	273	7.77	48.50	30.18	12.14	9.18	64.62	4.11	7.54	1.16	1.25	11432	
8	5.0200W	303	11.62	43.26	28.89	15.69	12.16	58.81	3.66	7.42	1.08	1.18	10398	
9	6.0402W	304	7.16	49.50	32.44	10.69	7.37	66.97	4.28	8.13	1.20	1.36	11983	
10	6.0200W	587	13.89	44.20	26.62	18.17	11.01	57.00	3.56	7.58	1.23	1.45	10010	
11	7.1610—	519	2.83	50.82	32.24	7.45	9.49	66.78	4.30	8.59	1.25	2.14	12012	

ite samples fairly represent the coal as delivered. Comparison of the amount of adhering moisture carried by washed coal can be justly made only by taking into account the lengths of haul in transportation, conditions of weather and the time since loading; so in this respect, only qualitative deductions should be drawn from the figures given for total moistures. Coal from the mine, Index No. 4, was usually delivered on the following day after washing and was loaded directly from the car into the boiler room. The coal from each of the other mines was several days in transit and was unloaded into roofed storage sheds. Test samples only were taken. The coal, 5.1006W remained in storage about six weeks before it was sampled.

Table 3 gives the results of analyses for the air-dry sample. These are original figures reported by the chemical laboratory. It is interesting to note that there is but small dif-

TABLE 3 AVERAGE COMPOSITION AND CALORIFIC VALUE
OF THE AIR-DRY COAL

Analyses of Composite Samples												
No.	Coal Symbol	Chem. Lab. No.	Air-Dry Samples									
			Proximate Analyses									Calorific Value per pound
			Fixed Carbon	Volatile Matter	Ultimate Analyses							
					Moisture	Ash	Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur	
1	2	3	4	5	6	7	8	9	10	11	12	13
			%	%	%	%	%	%	%	%	%	B.t.u.
1	4.0703W	608	48.45	37.53	5.27	8.75	68.65	4.56	9.77	1.14	1.86	12141
2	4.0703W	253	47.58	37.24	5.67	9.51	68.22	4.40	9.03	1.15	2.02	12122
3	4.0700W	302	45.99	38.50	4.95	10.56	66.95	4.39	10.01	1.15	1.99	12149
4	4.0300W	600	44.19	34.80	5.53	15.48	63.05	4.14	7.99	1.34	2.47	11086
5	5.1610W	502	53.68	33.76	3.79	8.77	70.90	4.82	9.12	1.25	1.35	12604
6	5.1006W	571	53.72	32.29	4.76	9.23	69.79	4.40	9.30	1.30	1.22	12381
7	5.0602W	273	52.59	32.72	4.74	9.95	70.06	4.46	8.18	1.26	1.35	12395
8	5.0200W	303	48.94	32.69	4.61	13.76	66.55	4.14	8.39	1.22	1.33	11765
9	6.0402W	304	53.32	34.94	3.80	7.94	72.13	4.61	8.76	1.29	1.47	12907
10	6.0200W	587	51.83	30.91	4.97	12.79	66.20	4.13	8.80	1.43	1.68	11625
11	7.1610—	519	52.30	33.18	4.75	9.77	68.72	4.43	8.84	1.29	2.20	12362

ference in the amount of absorbed moisture in the different coals after air drying. The method of air drying is explained on page 101.

Table 4 gives a better comparison of the characteristic differences in composition of the fuel from the two localities represented. For analyses and heating values used in the calculation of the test results, see Tables 37 and 38, Appendix III.

TABLE 4 AVERAGE COMPOSITION AND CALORIFIC VALUE
OF THE ASH AND MOISTURE-FREE COAL

Analyses of Composite Samples											
No.	Coal Symbol	Chem. Lab. No.	Pure Coal (Ash and Moisture-Free Coal)								
			Prox. Analyses		Ultimate Analyses						Caloric Value per pound
			Fixed Carbon	Volatile Matter	Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur		
			%	%	%	%	%	%	%	B.t.u.	
1	4.0703W	608	56.35	43.65	79.85	5.30	11.36	1.33	2.16	14121	
2	4.0703W	253	56.10	43.90	80.42	5.19	10.65	1.36	2.38	14291	
3	4.0700W	302	54.43	45.57	79.24	5.20	11.85	1.36	2.35	14380	
4	4.0300W	600	55.94	44.46	79.81	5.24	10.12	1.70	3.13	14035	
5	5.1610W	502	61.39	38.61	81.09	5.51	10.43	1.43	1.54	14416	
6	5.1006W	571	62.46	37.54	81.14	5.12	10.81	1.51	1.42	14395	
7	5.0602W	273	61.65	38.35	82.12	5.23	9.59	1.48	1.58	14529	
8	5.0200W	303	59.95	40.05	81.53	5.07	10.28	1.50	1.62	14412	
9	6.0402W	304	60.41	39.59	81.72	5.22	9.93	1.46	1.67	14622	
10	6.0200W	587	62.41	37.59	80.50	5.02	10.70	1.74	2.04	14135	
11	7.1610—	519	61.18	38.82	80.40	5.18	10.34	1.51	2.57	14462	

III. SUMMARY OF RESULTS AND CONCLUSIONS

7. *The conclusions* herewith presented are based on 58 trials with washed coal and 6 trials of No. 2 unwashed coal.

The grades tested were regular commercial grades purchased at the mine, and with one exception, in which a mixture of two grades was tested, were of sizes representing common standards. Tests of eight standard grades covering a full range of sizes suitable for burning upon the chain grate are included.

Much of the work has necessarily been of preliminary character, but an endeavor has been made to obtain as general a

survey of the facts relating to the use of washed grades in connection with the chain grate stoker as was possible with the time and funds available. In making an analysis of the work, particular emphasis has been placed upon the modifying influence of methods of furnace control, the variations in the results due to radiation and conduction losses from the furnace and boiler, and the factors that influence the relative values of the fuels. Data not directly applied to the analyses made are presented in Appendix III.

It is shown in the analysis that results of tests direct with steam boilers may be only roughly compared, and that if close comparison of evaporative results is to be made, the amount of radiation and conduction losses must be known and corresponding corrections applied.

8. Concerning the principal points investigated, the following general conclusions may be drawn:

1. A comparison of fuels burned upon the chain grate is possible only when the fuel beds are kept in uniform condition. Irregularities that may occur in the fuel bed, whether induced by characteristics of the fuel or otherwise, may cause variations in the evaporative results for the same grade, which are wider than occur between any grades above the size $\frac{3}{8}$ in. to 0, when those grades are burned with the best care and attention.

2. Under the best care of the fuel bed (horse-power, depth of fuel bed, and other imposed conditions being equal), representative grades show the following relative economic values, based upon ash and moisture free coal:

Laboratory File No.	Size inches	Relative Total Heat Values	Relative Practical Heat Values	Relative Economy
5.1610 W	1 $\frac{1}{4}$ to 1	1.021	1.036	0.981
7.1610 —	1 $\frac{1}{4}$ to 1	1.020	1.038	0.994
5.1006 W	1 to $\frac{3}{4}$	1.022	1.036	1.039
4.0703 W	$\frac{7}{8}$ to $\frac{3}{4}$	1.000	1.000	1.000
4.0300 W	$\frac{3}{8}$ to 0	0.984	.983	0.778
6.0200 W	$\frac{1}{4}$ to 0	1.000	1.004	0.813

The ratios shown are taken with respect to the results for fuel 4.0703 W, and economy values are compensated for radiation and conduction losses from the furnace and boiler.

The ratios for the economy include the variations due to size, unequal practical heat value, and ash-pit loss.

The sizes used represent the range of sizes that are practicable for the chain grate stoker. The widest variation in economy shown is that between fuel 5.1006W and fuel 4.0300W, approximately 26 per cent with a variation of 3.8 per cent in the total heat values, and a variation of 5.3 per cent in the practical heat values.

It should be noted that the ratios for relative economy represent only one factor in the money value of the grades. Large sizes, it is known, have better shipping and storing qualities and are suitable for a wide variety of uses. Very fine sizes, on the other hand, require greatest attention in burning and increase the stand-by losses and fixed charges of the plant.

3. The effect of size, *per se*, upon resulting economy and thermal efficiency, i. e., apart from variation induced by differences in initial heat values and losses of heat, is characteristically shown by the quantities of air accompanying combustion. The weight of air per pound of combustible consumed and the percentage of excess air for the several fuels, taking for comparison the same conditions and tests as are used in the comparison (2) above, are as follows:

Index No.	Size inches	Pounds of Air per pound of Combustible Consumed	Excess Air percent
5.1610 W	1 $\frac{3}{4}$ to 1	21.05	81.76
7.1610 —	1 $\frac{3}{4}$ to 1	21.18	79.39
5.1006 W	1 to $\frac{1}{2}$	17.93	51.81
4.0703 W	$\frac{1}{2}$ to $\frac{3}{8}$	17.30	54.34
4.0300 W	$\frac{3}{8}$ to 0	28.05	135.87
6.0200 W	$\frac{1}{4}$ to 0	31.56	169.47

The fact that the order of the values for "Excess air, per cent" is slightly different from the order of the quantities in column 3, is due to a slight difference in the chemical compositions and theoretical air requirements of the combustibles consumed.

These values represent a combined characteristic of the size and grade under conditions of operation that maintained the fuel beds of the same area and gave to each fuel the attention that seemed necessary to produce best eco-

nomic results. The excess air for all grades may be further reduced by banking the fuel at the back of the grate, but as that condition jeopardizes economy through increased loss of fuel in the ash and refuse, it was not attempted.

4. Any rate of combustion or horse-power desirable for stationary practice may be obtained with any of the standard grades tested above the sizes $\frac{3}{8}$ in. to 0.

With the sizes $\frac{3}{8}$ in. to 0 and $\frac{1}{4}$ in. to 0, the boiler rating was obtained approximately, as a maximum result. With one shipment of the grade $\frac{1}{4}$ in. to 0, 175 H. P. was obtained as a maximum. For these small sizes increasing the draft would not further increase capacity. Careful attendance in burning fine sizes pays a big premium.

5. Comparisons of rates of combustion or horse-power for different fuels should be made on the basis of equal rates of air supply. Comparisons in that manner are shown on page 65.

6. For sizes above $\frac{3}{8}$ in. to 0, a slight tendency toward increased excess of air with increased rate of combustion is indicated, though no systematic relation is shown.

The thermal efficiency decreases slightly with increased rate and apparently in a linear relation. The horse-power is approximately proportional to the rate of combustion. Various grades differ in this respect, according to the proportion of excess air accompanying combustion.

The fine sizes produce their best results generally at their maximum rate of combustion. The size $\frac{3}{8}$ to 0 (fuel 4.0300W) is superior in this respect to the size $\frac{1}{4}$ to 0 (fuels 5.0200W and 6.0200W).

7. Increasing the thickness of the fuel bed results in a decrease in the loss of fuel in the ash and refuse. In some cases there results also a slight decrease in excess air, but in other cases a slight increase results. No definite relation depending upon the size of the grade is shown in the latter respect.

The maximum difference shown in over-all efficiencies due to carrying different thicknesses of fuel bed is approximately 2 per cent for gate openings varying from 4 to 7 in.

IV. GENERAL CONSIDERATIONS AND DEFINITIONS

9. In the analysis of the performance of steam generators it is sometimes thought to be useful to define in some detail, the functions of the separate parts of the generator, such as the grate, the combustion space, the boiler, etc. The boiler is easily differentiated from the other parts of the steam generator, but to ascribe a definite division of duties to the furnace parts involves arbitrary assumptions and definitions. Consequently, terms vary in meaning in the literature of the subject and depend upon the view point of the writer. For the purposes of the present work, it will be necessary to make only one division, i. e., the boiler and the furnace and to define them as follows:

10. The *Boiler* is a definite arrangement of heating surfaces including any fixed arrangement of gas baffles that may be used for the purpose of directing the course of the heated gases over the heating surfaces.

The *Furnace* includes the combustion space, the grate or mechanical stoker, incidental brick work and enclosing walls.

Certain parts of the furnace, arches in particular, are essential for the ignition and proper combustion of the fuel in mechanical stokers and, in general, the form of the brick parts is determined by the stoker or the grate. The tile roof of the Heine combustion chamber is a feature of the boiler and also a feature of the furnace.

11. A division according to function is not so simple. The sole function of the boiler is to absorb heat, and with clean heating surfaces its characteristics are definite. In order that the heat in the coal may be actually available for transmission to the boiler, it must be developed and transferred in gases, or by radiation from the fuel bed and flames, at temperatures above that of the heating surfaces. Since a considerable part of the heat is always contained in the gases below the temperature of the heating surface, the economy of the process increases as the heat contained in the gases above the temperature of the heating surface increases. The available heat in the gases at any given temperature is, of course, only the heat that is used to increase the temperature of the gases, i. e., the so-called sensible

heat. However as the gases are cooled in their passage over the boiler surfaces, the part of the heat that was used in doing the work of expanding the gases in the furnace is directly used by the boiler. For lack of a more definite term, the term heat content used in the following discussion is taken to include both the sensible heat and the heat required for the work of expansion. The heat content is proportional to the temperature of the gases and the mean specific heat at constant pressure. Denoting by Q the heat content of one pound of the gases we have, therefore,

$$Q = C_p T.$$

The gases are the principal means of conveying heat to the boiler, when the furnace is of the kind used in this work, but where much heat reaches the surfaces by direct radiation, as in plain tubular, locomotive, and internally fired boilers, the problem is much complicated. It is intended, however, to deal here with a single type of plant in which there is reason to believe that but a small proportion of the total heat reaches the heating surface by direct radiation, i. e., by transmission through the tile roof. However, whether the process of heat transfer from the fuel to the boiler is by conduction from gases alone or is a mixed process, it is nevertheless true that economy in the utilization of the heat from the coal increases as the sensible heat content of one pound of gas increases.

12. *Furnace Effect.*—For brevity, and significance as well, the “heat content of one pound of the gases” delivered to the boiler will be termed the *furnace effect*. The factors that operate to modify the furnace effect are:

1. Total heat value of the coal.
2. Latent heat in the moisture formed by the burning of the hydrogen in the coal.
3. Latent heat in the moisture evaporated from the coal.
4. Undeveloped heat in smoke and incompletely burned furnace gases.
5. Proportion of air supplied to fuel consumed.
6. Radiation and conduction from the furnace parts.
7. Loss of heat in hot ash and refuse.

The first, second, and third factors determine the quantity of heat from the coal that will be available for producing rise of temperature. The total heat value of a coal as determined by means of the combustion bomb calorimeter is the heat that would be available by cooling the combustion gases to the temperature at which the combustion was initiated, i. e., room temperature—usually about 70° F. Thus the heat that becomes latent in furnace processes is included in the reported total heat value of the coal.

The total heat minus the latent heat of the moisture is usually termed the *practical heat value* of the coal. It may be calculated as follows:

Let H = the total heat value, B. t. u. per lb.

m_1 = the moisture in the coal by weight per lb. of coal.

m_2 = the moisture formed in the burning of the hydrogen by weight per lb. of coal.

Then Practical heat value = $H - 966 (m_1 - m_2)$

Ash and moisture in coal are extremely variable and may be considered extraneous and as adding nothing of value. They are properly considered as diluents in considering heat values and may thus readily be taken account of in the purchase of coal. Because of the variability of ash and moisture content and the ready manner in which they may be accounted for by simple analysis, comparison of the practical effects of different types of coals is most satisfactorily based upon the unit of "combustible", i. e., ash and moisture free coal. This unit is termed by some writers "pure coal"; the usual designation combustible as used in the A. S. M. E. code is adhered to herein.

To give a rough idea of the variation in the furnace effect due to differences in practical heat values per unit of combustible, consider two Illinois coals having heat values of 13950 and 13500 B. t. u. respectively, and assume an air supply of 14 pounds per pound of combustible. Thus approximately 15 pounds of gas is formed and neglecting radiation and conduction losses, etc., the furnace effects are 930 and 901 B. t. u., respectively.

The quantity of air used, however, may vary between 14 lb. and 40 lb., giving with the latter quantity furnace effects of 340 and 330 respectively, for the two combustibles. In bad furnace operation as much as 50 pounds or more of air used per unit of combustible is not infrequently found. This illustration has been given to show the relative influences of the fifth factor given above and of the heat values of coals.

The effect of a higher heat value in coal must, of course, be a beneficial one, but the evaporative effect obtained in actual operation at times due to conditions that cause disproportion of the air supply may indicate even the reverse. The decrease in the furnace effect due to radiation and conduction from the furnace varies with the area of the exposed wall surface of the setting, the temperature within the furnace, specific conductivity of the walls, temperature of the surroundings, and drafts of air through the boiler room. Its real value in any instance has never been directly determined.

The fourth and fifth factors, it is well understood, can be modified either in the direction of good effect or of bad effect by the features of the furnace, the fuel, and the manner of operating the furnace. The importance of the proper proportion of the air supply has been indicated. The proportion of air to fuel consumed is affected by care or indifference in operating, mechanical conditions of the fuel, and leakage around the edges of the grate. These same conditions play an important part in determining the amount of smoke and incompletely burned furnace gases. The construction of the grate or mechanical stoker and the combustion space are important elements in determining the latter factor. Conditions affecting air proportion, smoke and incomplete combustion vary from those of poorly constructed and poorly operated hand-stoked furnaces and mechanically-stoked furnaces to excellent construction and operation in both, but whether a hand-stoked furnace or a mechanically-stoked one, the personal factor of the operation does not lose its importance.

The seventh factor may be disposed of as negligible for practical purposes.

This involved condition of affairs makes it impossible to assign the function of producing good furnace effect to any one element alone, or, on the other hand, to assign to any single element a function not involved in the function of other elements.

13. *Service Value of a Fuel.*—In view of the involved nature of the influences just noted, it will easily be understood why the application of the results obtained in evaporative tests of fuels is restricted in application to the particular types and combination of boiler and furnace in connection with which the tests were made, and further are especially restricted by the particular conditions of the furnace control.

For the purpose of comparing the economy of fuels, the heat absorbed by the boiler per pound of fuel should be based upon the fuel fed to the furnace. The results then take into account the loss of fuel from the grate. Conditions of the furnace operation in comparative tests are usually either very carefully controlled or they are the usual operating conditions in the plant where the tests are made. In either case loss of fuel in the ash and refuse is chargeable to the character of the fuel, the characteristics of the grate in that respect, and the conditions of operation. In a summary of experimental results, page 50, the term "service heat value" is used to designate the value of the fuel as found under test with a particular combination of boiler and furnace, operated under specifically controlled conditions.

By the term "service heat value" is meant the quantity of heat (B. t. u.) absorbed by the boiler and delivered to the steam per pound of fuel fed to the furnace. The expression of the economic result in B. t. u. is more convenient for comparison with the total heat value of the fuel than if expressed in pounds of water evaporated per pound of fuel. Otherwise, either manner of expressing the economic result is equally useful.

The heat absorbed by the boiler depends mainly upon the furnace effect and whatever modifications of results are due to the characteristics of the boiler. When, however, the resulting absorption is expressed on the basis of one pound of fuel, the heat delivered to the boiler per pound of fuel is a measurable factor. It is the difference between the total heat value of the fuel and the sum of the losses due to incomplete combustion, latent heat in moisture, loss of fuel from the grate and radiation and conduction losses from the furnace. The furnace effect is equal to this difference divided by the number of pounds of moist combustion gases resulting per pound of fuel. Evidently it is possible in two different operations to have equal furnace effects with unequal quantities of heat delivered per pound of fuel. This condition may result from a difference in the initial heat value of the fuel or a difference in the sum of the losses. Necessarily different weights of gas per pound of fuel will be required in two cases: and since the rate of heat transmission depends upon the temperature of the gases above the temperature

of the heating surface a different heat absorption per pound of fuel must result.

14. *Efficiencies*—Two expressions for efficiency are used in this report. They are termed respectively:*

Over-all efficiency, E_1 .

Efficiency of the boiler and furnace, E_2 .

The reason for adopting these terms in place of the usual ones which are given in the code of the A. S. M. E. for boiler testing, should be evident from the preceding remarks. The A. S. M. E. code expressions are:—

“Item 72. *Efficiency of boiler*: heat absorbed by the boiler per pound of combustible consumed divided by the heat value of one pound of combustible = Item (71 x 965.8) — Item 51.”

“Item 73. *Efficiency of boiler, including the grate*: heat absorbed by the boiler per pound of dry coal fired, divided by the heat value of one pound of dry coal

= Item (70 x 965.8) — Item 50.”

Item 72, as it is now defined in the A. S. M. E. code, is not the efficiency of the boiler alone, but includes also the furnace, the influence of the fuel characteristics, and the variation and faults of operation; in fact, all of the factors that cause variation in the value found for Item 73 with the exception of the ash-pit loss. That is, Item 72 and Item 73 are identical in their main import; they are both measures of composite effects, the only difference being that in Item 73 a charge is made against the plant for the heat of the total weight of fuel fired while in Item 72 the charge against the plant excludes one variable.

E_1 is calculated herein in the same manner as in the A. S. M. E. code Item 73, and E_2 is calculated in the same manner as the A. S. M. E. code Item 72, and in the report these item numbers are used to designate them. The only difference is in the less ambiguity of the terminology. As a matter of fact, the term “boiler and furnace” efficiency is ambiguous unless it is kept in mind that it is merely the over-all efficiency compensated for the ash-pit loss.

In the discussion of results and in Tables 5 to 14 these efficiencies have been compensated for the heat lost in the water-back,† the corrected items being designated by “Item 72.1” and “Item 73.1.”

*These terms were suggested by L. P. Breckenridge, Jour. W. Soc. of Engrs. XXII. 3, 288.

†See pages 115 and 116.

15. *Rate of Combustion.*—From the standpoint of theoretical chemistry, each constituent in the heterogeneous mixture of carbon and hydrocarbons which make up coal substance should, under isothermal conditions, have a definite velocity with which it will react with oxygen. And, in general, the different components have different rates of reaction, the more so because many of the hydrocarbons wholly oxidize only after volatilization and subsequent successive changes in chemical structure.

Oxidation of these compounds takes place slowly at ordinary temperatures, but at temperatures approaching those of industrial furnaces, the velocity of oxidation is so enormously accelerated that we never note any practical difference in the rate of combustion chargeable purely to differences in the velocity of oxidation of different fuels.

Experience shows that as rapidly as we can supply air to the fuel it will be burned. Differences in rate of combustion in a practical sense are wholly due to conditions that prevent the air from coming in contact with the fuel, and to the amount of air supplied.

With fine sizes of coal the rate of combustion is limited by the rate of air supply that disrupts the fuel bed and permits air to pass through without coming into contact with the fuels. This limit is reached with very fine-sized coals and with screenings containing much dust, and is a serious circumstance in steam generation because of a natural tendency of the fireman to increase the draft when there is demand for more steam. This maximum limit in the rate of combustion is one of the important factors which determine the selection of fuel for a particular condition of service. To discover just what this maximum limit is and to determine its relation to the draft pressure is an essential item to be observed in experimental testing.

For those grades of fuel that do not exhibit a maximum rate of combustion within the limits of practical demands, and below that limit for those that do, it is important to know the relation between characteristics of the grade, the draft conditions, and air supply. For a useful and practical consideration of these features, it is imperative that the following points should be recognized.

In a practical sense the weight of fuel that can be burned in a given time is determined by two principal factors.

(a) The rate at which air is supplied to the fuel.

(b) The efficiency with which the air is utilized.

The relation of these two factors is apparent at once, for if we consider two equal fuel bed areas to be supplied with the same volume of air per unit time, that one will be most rapidly consumed which utilizes the air most completely. On the other hand if the air in both cases is utilized to the same extent, the relative rates of combustion will be directly proportional to the rate of air supply.

The first factor (a) is the one most usually considered as determining the rate of combustion. The second factor (b) is rarely given proper consideration. Its significance will be seen when it is recalled that for a given rate of air supply, the rate of combustion will be approximately twice as great with 12 per cent of carbon dioxide in the flue gases as with but 6 per cent.

The second factor (b) is that to which we have charged the variations in the furnace effect, and the same causes, viz., character of the fuel, leakage, degree of care in attendance, which affect the furnace effect by dilution of the combustion gases, act under fixed draft capacity to modify the rate of combustion.

The first factor depends upon the resistance of the fuel bed and grate, and the available draft pressure and draft capacity. The resistance of the fuel bed varies with the size of the fuel, the thickness of the fuel bed and the amount and character of caking and clinkering.

V. TEST RESULTS

16. As stated elsewhere in the discussion of results, the present report is concerned with that part of the data most directly related to the fuel. In Appendix III many data are presented which, it is hoped, aside from the intrinsic value, may be found useful to those who may wish to review the work critically.

Limitations of results. In comparing the characteristics of the different grades of coal, it has been a problem of serious concern as to how much attention should be given to the fuel beds.

Some fuels require little attention, while others have a characteristic tendency to burn out in spots or clinker more or less seriously. The furnace attendant naturally judges the quality of the coal by the amount of attention required to keep up steam. Thus, since this feeling is a general one, it would be of interest to compare fuels under equal attention all around for certain special plant conditions. To adopt such methods for test purposes, however, would be to place upon large grades of coal a premium which they do not deserve, when market prices are considered. Moreover, a hesitating demand for certain of those grades which require much attention has been a factor in maintaining them as cheap fuels, although more than sufficient pecuniary advantage to offset the extra care required may be obtained from their use.

17. Mechanical stokers, which feed by continuous progression of the fuel over the surface of the grate, or in which the grate itself progresses through the furnace, and which are therefore continuously self-cleaning, are adapted to a wide range of fuels. A feature of these self-cleaning types is the difficulty of proportioning the air supplied to the furnace, especially when the fuel is not uniform or is of very fine size. The nature and depth of the fuel bed changes gradually from the feed gate to the end of the grate, and an excess of air is admitted where least needed by the fuel. The stirring action of inclined stokers, though an advantage with mildly coking coals, is unnecessary with moderately free-burning coal and tends to distribute the air unevenly. Combustion upon the chain grate is free from this particular source of dilution since the fuel bed may remain undisturbed during combustion. Excess air through the thin fuel bed at the rear of the grate, and leakage into the furnace between the bridge wall and the end of the grate, or through the dump grate of the inclined stoker can not be readily controlled. Devices applied to the chain grate for preventing undue leakage, such as over-hanging bridge walls with or without water-backs, designed to permit just sufficient room for the passage of the ash, and the various forms of dampers under the grate and in the ash-pit, are only moderately successful.

A feature of such mechanical stokers, which largely operates to offset the disadvantages just noted and which make them particularly adapted for efficient combustion of high volatile coals, is the ignition arch under which the fuel passes as it enters the

furnace. On account of the depth of the fuel bed under the arch, the air supply there is retarded and is insufficient for the complete combustion of the volatile matter distilled off in large amount at that place. If the combustion space is properly constructed, this volatile matter can mix with the diluted gases from the thinner portion of the fuel bed and be burned. Thus a proper proportion of excess air through the rear portion of the fuel bed is an advantage.

In the case of the traveling grate, the importance of carefully standardizing the furnace control in practical testing is emphasized by the following fact. By driving the grate faster than the fuel is consumed and thus passing burning fuel over the rear end into the ash-pit, the excess air at the rear end may be largely utilized, and the result is, of course, a higher furnace effect and consequently higher "boiler and furnace" efficiency, but because of loss of fuel the over-all economy is decreased. This possibility is sometimes taken advantage of in tests in which it is desired to show a high "boiler and furnace" efficiency with a given coal, and in practical operation under conditions where the demand for high boiler horse-power temporarily sets aside considerations of economy.

18. *Control of the Furnace.*—In outlining the tests of these experiments an effort was made to so standardize the operating of the furnace that the details of the control during each test might be made a matter of record. General features of the furnace control, which should be noted because of their bearing upon the test results, are set forth in the following paragraphs.

19. *Depth of the Fuel Bed.*—This was taken as the depth of the gate opening since an accurate estimate of the average depth of the grate could not be made.

20. *Area of the Fuel Bed.*—The area of the fuel bed was maintained as nearly as possible the same for all fuels, regardless of the frequency of adjustment required by the stoker-driving engine. Throughout all the tests, it was specifically understood that the fuel should not be allowed to bank against the water-back nor the live fuel line recede from the water-back a greater distance than was absolutely necessary. An attempt was made to hold the live fuel about 4 inches short of the water-back: the regulation of the small stoker engine, however, could not be depended upon so that this condition could not be exactly met. The difficulty was augmented in the early tests by trouble with the draft engine and by the conditions under which those tests were made.

21. *Attention Given to the Fuel Bed during Operation.*—During the tests No. 1 to 20 attention to the fuel bed was confined to occasional leveling. The object was to observe the performance with minimum attention to the fuel beds. At no time, however, were irregularities in the fuel bed allowed to become serious. During tests No. 20 to 64, it was sought to bring out the best possibilities with each fuel. In these tests, thin spots and humps at the rear edge of the bed were leveled and fuel was frequently pushed against the ledge plates to regulate leakage of air.

22. *Regulation of Draft Pressure.*—The following convention was adopted to define the draft pressure of the furnace. The *normal draft pressure* is that pressure upon the fuel bed which exists when the fuel bed is of the regular area assigned for all tests, when the fuel bed is without thin spots, and when the leakage along the ledge plates is not greater than normal. A normal draft pressure was assigned for each test on the day previous to the date of the test. This made it possible for the firemen to regulate the conditions some time before the start.

23. *Rate of Combustion.*—As closely as possible an even rate of combustion was maintained throughout each test.

24. *Fine Coal From the Drip Plate.*—The fine coal which fell through the grate was returned to the feed hopper and again fed to the furnace. This was done more frequently than usual under ordinary plant operation, the attempt being to distribute the fine coal uniformly.

25. *Leakage at the Rear of the Grate.*—The automatic water-back in all tests except one was allowed to ride upon the ash and clinker, so that the leakage of air passing to the furnace over the rear of the grate was as nearly as possible independent of the character of the fuel and other conditions save the draft pressure.

26. The record of the furnace conditions was carefully kept during each test. An explanation of the furnace record is given on page 92, and Table 40, Appendix III, comprises a summary of as much of the data contained in those records as is possible to represent in tabular form. Essential parts of the record which could not be so summarized have been kept in mind in modifying conclusions concerning the fuels.

VI. ANALYSIS OF RESULTS

27. For purpose of more ready comparison, important items from Tables 28 to 40, Appendix III, together with items not elsewhere presented, are set forth in this chapter, and certain of the relations shown graphically by means of charts. General explanations of the tables and charts follow.

28. *Tables.*—At the head of each table is given the fuel index number. The commercial sizes in fractions of inches are given in Table 1, page 4.

Column 1, series test number.

Column 2, depth of fuel bed in inches.

Column 3, draft pressure on the fuel bed in inches of water. This is the drop in pressure through the fuel bed. See page 116.

Column 4, pounds of combustible consumed per square foot of grate surface per hour = code item 30 $\div$ 38.2.

This item represents the actual combustion. For the purpose here intended it is a better expression for the rate of combustion than "pound of dry coal per square foot of grate surface" since it removes non-essential variations due to differences in the percentage of ash and in the loss of fuel to the ash-pit.

Column 5, Horse-power developed, Item 65.1. In this column the actual horse-power developed is compensated for the heat lost to the water-back as explained on page 106. Its use removes a minor variation of from 1 to 3 per cent due to that loss. The items are derived from Item 65, Table 34.

Column 6, Horse-power developed per square foot of grate surface = Item 65.1 $\div$ 38.2.

Column 7, Per cent of builders' rating developed = Column 5 $\div$ 210.

Column 8, Efficiency of "boiler and furnace". See Item 72.1 page 115 and Table 35.

Column 9, Over-all efficiency. See Item 73.1 page 116 and Table 35.

Column 10, Per cent of total combustible lost in the "ash and refuse" = (Item 31 $\times$ Item 44) $\div$ (100 — Item 42). See Tables 29 and 38 for Items 31, 42, and 44.

Column 11, per cent of CO_2 in dry flue gases. See Table 36 and page 117.

29. The graphical representation of data presented in these tables is shown in Fig. 1 to 9.

These curves are not to be taken as representing mathematically definable relationships, and for this reason it may not be without value to call attention to the following considerations. For the most part the curves represent functions of two or several variables. For example, plotted points for the amount of air used per pound of combustible consumed and the resulting gas composition, should be expected to show only whether the excess of air varies with the rate of combustion and draft pressure. Since the drop in draft pressure is largely affected by the velocity or volume of gas flowing and its temperature, plotting points for this drop against rate of combustion is not wholly illogical, and reference to the points on the carbon dioxide curve or air supply curve will generally indicate the principal cause of variation. The carbon dioxide resulting from the combustion of a uniform coal composition is a function practically of the weight of air used per pound of combustible consumed, and with a constant per cent of CO_2 the volume of air flowing gives a directly proportional rate of combustion.

The general relation of these various factors, one to the other, is not difficult to understand, though the practical mathematics of the relations is somewhat tedious and will not in general permit of exact or in some cases even approximate interpolation between plotted points affected by a third variable; yet with proper consideration, the curves illustrate sufficiently well the relations under the conditions of the experiments. The resulting carbon dioxide percentages have been plotted in each of the charts as a datum of reference. The relation between the per cent of carbon dioxide and the furnace effect and temperature of combustion is very nearly a direct proportion, so that it will be apparent at once that the possibility of representing the data for certain fuels in the form of smooth curves has depended largely upon slight variation in the carbon dioxide conditions. In the charts showing air supply and draft pressures, uniformity of the fuel and furnace operation adds to the uniformity of the curves. The values for air

supply data are given in Table 24, page 72. Graphical representation is made only for those fuels that were tested at various rates of combustion.

30. *Fuel 5.0602 W*, Table 5.—Fuel of this grade, commercially known as No. 4 washed coal, is very uniform, and when it is burned upon the chain grate, the fuel bed usually requires little attention beyond care in the regulation of the grate and the occasional removal of clinker accumulating along the ledges. The tests of this fuel included in Table 5 were conducted under conditions of ordinary careful furnace control. Table 34 should be referred to.

TABLE 5 FUEL 5.0602W

Test No.	Depth of Fuel Bed Inches	Draft Pressure on Fuel Bed Inches of Water	Lb. of Combustible Consumed per sq. ft. of Grate Sur- face per hr.	Horse Power Developed Item 65.1	Horse Power Developed per sq. ft. of Grate Surface	Per cent of Builders Rating Developed Item 67.1	Efficiency of "Boiler and Furnace" Item 72.1	Over-all Efficiency Item 73.1	Per cent of Total Combustible Lost in "Ash and Refuse"	Carbon Dioxide in Flue Gases Per cent
1	2	3	4	5	6	7	8	9	10	11
6	4	0.102	19.74	218.4	5.71	104.0	66.66	64.72	2.91	* 7.04
7	4	0.104	20.89	232.5	6.09	110.7	67.12	63.60	5.32	* 10.10
8	5	0.090	19.71	216.3	5.66	103.0	66.16	64.42	2.63	* 9.54
9	6	0.134	20.65	215.8	5.64	102.8	62.93	61.87	1.74	* 9.47
10	7	0.162	20.13	210.5	5.51	100.2	63.09	62.00	1.73	* 6.22
11	6	0.150	20.16	216.3	5.66	103.1	64.38	62.91	2.20	* 8.05

*See page 117.

Four thicknesses of fuel bed were tried. The resulting efficiencies are in favor of the 4- and 5-in. beds. The smaller values for the 6- and 7-in. beds are due in part to irregularity of grate performance. On the whole, the furnace control for tests 9, 10 and 11 was less favorable to the fuel than that for tests 6, 7 and 8.

In all these tests, as will be noted generally, the greater ash-pit losses occur with the thinner fuel beds. The flame from this fuel was practically burned out at the rear of the combustion chamber, and no smoke was observed save in tests 10 and 11 at times when the fuel was banked against the water-back. See definition of "banked", page 94. The smoke for those periods was less than the shade represented by Ringelmann chart No. 2,

the average for each test being 0.08. See Column 12, Table 36. No trouble of any sort was experienced from clinker.

From the test results, it must be concluded that this fuel may be burned with no attention to the fuel bed, with resulting "boiler and furnace" efficiencies from 64 to 67 per cent, and over-all efficiencies from 62 to 65 per cent. With better attention to the fuel bed and more uniform regulation of the grate travel, this fuel would give as good results as those of Tables 8 and 14.

31. *Fuel 5.0200 W*, Table 6.—Washed coal of this grade passing a $\frac{1}{4}$ -in. round hole screen is generally known as No. 5 washed coal. Though made up of a narrow range in sizes, the proportion of intermediate sizes and especially the amount of dust contained may vary considerably in the washing process, and for this reason considerable variation in results must be expected even with coal from the same washery. The coal forms a very compact fuel bed, so that these slight changes in the proportion of intermediate sizes may produce a very considerable variation in the draft requirements. Six tests were made on this coal to determine the conditions favorable to maximum rate of combustion and evaporation. As in the preceding tests, the furnace control was that of good plant practice.

TABLE 6 FUEL 5.0200W

Test No.	Depth of Fuel Bed Inches	Draft Pressure on Fuel Bed Inches of Water	Lb. of Combustible Consumed per sq. ft. of Grate Sur- face per hr.	Horse Power Developed Item 65.1	Horse Power Developed per sq. ft. of Grate Surface	Per cent of Builders Rating Developed Item 67.1	Efficiency of "Boiler and Furnace" Item 72.1	Over-all Efficiency Item 73.1	Per cent of Total Combustible Lost in "Ash and Refuse"	Carbon Dioxide in Flue Gases Per cent
1	2	3	4	5	6	7	8	9	10	11
12	5	0.270	20.18	179.5	4.70	85.5	54.08	49.76	7.98	*7.10
13	6	0.380	21.54	193.6	5.07	92.2	54.47	51.14	6.12	*6.40
14	6	0.430	21.65	195.5	5.12	93.0	54.84	51.96	5.11	*5.84
15	4	0.390	24.01	216.8	5.67	103.2	54.88	49.17	10.32	*7.02
16	4	0.270	22.62	207.3	5.43	98.7	55.76	49.95	10.27	*5.95

*See page 117.

On account of the fineness of the coal and because of the closeness of the fuel bed, fuel of this size burns best when the force of the air passing through the fuel is sufficiently great to keep the finer particles continually agitated. To carry the draft much beyond this results in trouble. Holes develop rapidly, the increasing rush of air through such spaces reduces the draft pressure, and the rate of combustion is retarded over the entire bed. Reducing the draft much below the best condition not only retards the combustion, but gives the leakage of free air along the ledge plates and at the back of the grate an increasing weight in the total.

The proper draft pressure for the 6-in. bed was between those used. Practically the same rate of combustion was obtained with draft pressures of 0.38 and 0.43 respectively. In test 13 the fuel bed was dead and without serious tendency to form holes, as shown by the data in columns 9, 10 and 11, Table 40, while in test 14 considerable trouble resulted from the formation of holes over the back half of the grate, and the draft pressure varied widely at times. Tests 15 and 16 with a 4-in. gate opening gave most uniform results throughout, but required a high speed of grate travel. See Table 40. The chief trouble with a 4-in. bed was the tendency to burn out at the back end, requiring very careful regulation of the grate travel. For practical purposes a 4-in. fuel bed is too thin for this grade. With the 5-in. gate opening, test 12 gave very satisfactory results in every way except that the draft pressure was too low for maximum results. This was shown by the dull flat appearance of the fuel bed.

From these tests, the general conclusion can be drawn that under good plant practice there may be developed with this fuel for each square foot of grate surface, from 4.5 to 5.5 horse power at "boiler and furnace" efficiencies from 54 to 56 per cent, and over-all efficiencies from 49 to 52 per cent.

32. *Fuel 4.0700 W*, Table 7.—This fuel is a combination of the two grades, 4.0703W, Table 14, and 4.0300W, Table 13, the mixture containing about 30 per cent of the latter. At the washery, the component grades are washed separately and upon special order combined in varying proportions by running the products into the same bin. Subsequent handling in loading and unloading is depended upon to give a uniform mixture. On account of a fairly even gradation of sizes and the wet condition of the coal, this is ordinarily sufficient.

It was not intended at the time these tests were made, to extend the work to include mixtures of the standard commercial grades, but this car having been received by a mistake in billing, the four tests were made in view of the indications they might give as to the advisability of taking up such a series, and in that connection the results are interesting.

The tests were made under essentially the same conditions as those of Table 5, but the control of the fuel bed area, affected by more uniform regulation of the grate travel, was superior.

TABLE 7 FUEL 4.0700W

Test No.	Depth of Fuel Bed Inches	Draft Pressure on Fuel Bed Inches of Water	Lb. of Combustible Consumed per sq. ft. of Grate Surface per hr.	Horse Power Developed Item 65.1	Horse Power Developed per sq. ft. of Grate Surface	Per cent of Builders Rating Developed Item 67.1	Efficiency of "Boiler and Furnace" Item 72.1	Overall Efficiency Item 73.1	Per cent of Total Combustible Lost in "Ash and Refuse"	Carbon Dioxide in Flue Gases Per cent
1	2	3	4	5	6	7	8	9	10	11
17	5	0.130	19.92	213.3	5.58	101.6	65.31	62.23	4.71	*10.50
18	5	0.130	20.18	225.1	5.89	107.2	67.79	65.42	3.56	*10.60
19	4	0.106	20.39	224.9	5.89	107.0	67.04	64.69	8.66	*11.20
20	6	0.145	20.73	228.6	5.98	108.8	66.80	64.68	3.33	* 9.94

*See page 117.

This fuel burned with as great uniformity as fuel 4.0703W or 5.0602W, but required slightly higher draft pressure. The fuel bed remained in good condition, though burning more rapidly along the ledge plates. It will be noted that the ash in this coal was greater and more irregular, due, no doubt, to the admixture of the finer size, but it appears to have had no effect on the economy or to have caused trouble from clinker. Combustion was complete and without smoke, and in every respect the tests of this fuel indicate that it is as suitable for use with the chain grate as either the fuel 4.0703W or the fuel 5.0602W. How much the rate of combustion may be increased over that shown by the tests can not be exactly stated. Nevertheless, close observation of furnace conditions leads to the conclusion that at least 25 pounds per

square foot is possible, a value which represents approximately seven boiler horse-power per square foot of grate surface. There is also no apparent reason why the economy obtainable with this mixture may not be increased by increased attention to the fuel bed.

33. *Fuel 6.0402W*, Table 8.—The tests here included are the first of the series in which the fuel bed was given the attention

TABLE 8 FUEL 6.0402W

Test No.	Depth of Fuel Bed Inches	Draft Pressure on Fuel Bed Inches of Water	Lb. of Combustible Consumed per sq. ft. of Grate Sur- face per hr.	Horse Power Developed Item 65.1	Horse Power Developed per sq. ft. of Grate Surface	Per cent of Builders Rating Developed Item 67.1	Efficiency of "Boiler and Furnace" Item 72.1	Over-all Efficiency Item 73.1	Per cent of Total Combustible Lost in "Ash and Refuse"	Carbon Dioxide in Flue Gases Per cent
1	2	3	4	5	6	7	8	9	10	11
21	6	0.127	19.74	233.0	6.10	111.0	70.92	67.84	4.35	*12.40
22	7	0.138	19.03	218.4	5.72	104.0	68.46	66.98	3.01	*11.01
23	5	0.105	17.28	207.6	5.43	98.9	72.24	68.90	4.63	*11.79
24	4	0.085	19.55	232.3	6.08	110.6	71.65	68.56	4.31	*12.08
27	6	0.122	20.24	226.2	5.92	107.7	67.25	65.84	2.11	*9.60

*See page 117.

that seemed necessary to keep it in uniform condition. Reference to Table 40 will show that undoubtedly more leveling was done than necessary. This fuel is similar in all respects, as to composition and grade, to the fuel 5.0602W of Table 5; both are from the same seam in Williamson county.

As with the fuel of Table 5, all of these tests were run at about the rated capacity of the boiler. There can be no question, however, that any capacity desirable can be obtained with this grade.

In test 27 of this group, the water-back worked stiffly and had to be supported free from the fuel bed. The test should be excluded for that reason. The remaining tests show but small differences in efficiencies with reference to the thickness of the fuel bed, what advantage there is being with the thinner fuel beds, though the tendency toward increased ash-pit loss with the thinner beds is again indicated. No trouble was experienced with clinker, and though the flame extended through the combustion chamber, the fuel was burned without smoke.

34. *Fuel 5.1610 W*, Table 9.—This fuel is a larger grade of washed coal than is usually burned upon the chain grate. That it

TABLE 9.—FUEL 5.1610W

Test No.	Depth of Fuel Bed Inches	Draft Pressure on Fuel Bed Inches of Water	Lb. of Combustible Consumed per sq. ft. of Grate Sur- face per. hr.	Horse Power Developed Item 65.1	Horse Power Developed per sq. ft. of Grate Surface	Per cent of Builders Rating Developed Item 67.1	Efficiency of "Boiler and Furnace" Item 72.1	Over-all Efficiency Item 73.1	Per cent of Total Combustible Lost in "Ash and Refuse"	Carbon Dioxide in Flue Gases Per cent
1	2	3	4	5	6	7	8	9	10	11
25	6	0.122	17.88	204.7	5.36	97.4	68.16	64.47	5.43	*10.30
26	6	0.122	20.10	227.1	5.95	108.2	67.97	65.35	3.85	*10.00
28	7	0.145	19.35	213.7	5.59	101.8	66.38	65.19	1.82	** 8.88
29	6	0.124	19.06	209.6	5.48	99.8	66.28	64.52	2.69	** 8.88
30	5	0.103	19.61	215.3	5.64	102.5	66.14	64.18	2.96	9.38

is not commonly burned is due, however, to a relatively higher market price and not to any difficulties arising from its use. Except for minor variations in the area of the fuel bed for tests 25 and 26, the conditions under which these tests were run were exceptionally uniform.

Attention should be directed here to the change in the methods of taking gas samples in the interval between tests 27 and 28. A source of leakage in the gas samples was detected and remedied during test 29.

The results of tests 28, 29 and 30 are accepted as representing the comparative economy obtainable with this grade of fuel under the conditions of these tests.

But five tests could be made with this fuel and these were given over to the determination of the effect of thickness of the fuel bed. It is well known that rates of combustion may be obtained with this fuel far beyond any present practical requirements. Referring to the three directly comparable tests 28, 29 and 30, a tendency toward increased ash-pit loss and decreased over-all efficiency with decreasing thickness of fuel bed will be noted. No variation in the boiler and furnace efficiency is shown. See effect of radiation and conduction losses, page 52.

*See page 117.

**Leak in gas sampler.

This fuel ignites readily under the arch. A long flame results but with combustion completed within the combustion chamber. The percentage of clinker was very small and after experience in the first two tests, the regulation of the grate and fuel bed was easily maintained

35. *Fuel 7.1610 Unwashed*, Table 10.—This coal and the washed coal of Table 9 were obtained from mines located about two miles apart at Herrin, Illinois. Both belong to No. 7 seam and are of the

TABLE 10 FUEL 7.1610—

Test No.	Depth of Fuel Bed Inches	Draft Pressure on Fuel Bed Inches of Water	Lb. of Combustible Consumed per sq. ft. of Grate Sur- face per hr.	Horse Power Developed Item 65.1	Horse Power Developed per sq. ft. of Grate Surface	Per cent of Builders Rating Developed Item 67.1	Efficiency of "Boiler and Furnace" Item 72.1	Over-all Efficiency Item 73.1	Per cent of Total Combustible Lost in "Ash and Refuse"	Carbon Dioxide in Flue Gases Per cent
1	2	3	4	5	6	7	8	9	10	11
31	5	0.093	19.32	216.2	5.66	103.0	65.90	64.40	2.45	9.32
32	6	0.124	18.90	212.0	5.55	101.0	67.82	66.35	2.30	*9.00
33	7	0.143	20.44	223.7	5.86	106.6	65.97	64.56	2.15	9.40
34	8	0.116	21.02	231.9	6.07	110.4	66.13	64.58	2.31	9.47
35	6	0.157	23.40	253.0	6.62	120.4	64.48	63.12	2.14	9.62
36	6	0.188	26.05	275.0	7.20	131.0	63.81	62.35	2.25	9.02

same ultimate chemical composition and heating value and in every respect similar, with the exception of a slightly greater ash and sulphur content in the unwashed coal.

The small difference in ash content did not warrant any expectation of different results in the combustion tests, yet to satisfy any doubt, tests 31, 32 and 33 were made under conditions similar to those of tests 28, 29 and 30.

The occurrence of clinker, though not serious with either fuel, called for some extra attention in burning the unwashed fuel, as shown in column 7, Table 40; otherwise the results are similar.

The remaining tests of this coal were run at increased rates of combustion. Comparison of the six tests in that respect show no positive change in the results charged to the fuel and stoker.

*Slight dilution of sample due to leak.

In Fig. 1, the difference of draft pressure between the furnace and damper, designated curve 2, is plotted for tests succeeding test 30. See page 32. The points are obtained by taking the difference between columns 3 and 4, Table 36.

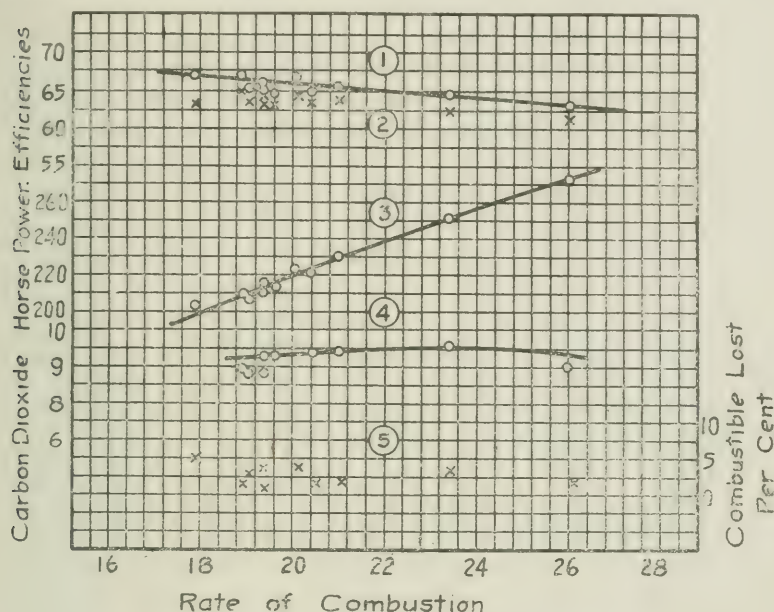


FIG. 2. TESTS OF FUELS 5.1610W AND 7.1610—

1. "Boiler and furnace" efficiency, E_2 , per cent.
2. Over-all efficiency, E_1 , per cent.
3. Horse-power developed.
4. Per cent of carbon dioxide in the flue gases.
5. Per cent of combustible lost in the "ash and refuse".

In Fig. 2, results for all tests of fuel 5.1610W and fuel 7.1610 — are plotted. It shows that the rate of evaporation or horse-power developed is directly proportional to the rate of combustion. The variation of points from the mean curves for horse-power and efficiencies shows a general relation to the variation in the per cent of carbon dioxide.

A long flame results with this fuel, but even at the higher rates there was no smoke or other evidence of incomplete combustion.

From the standpoint of uniform operation, the most satisfactory rate of combustion is in the range above 21 lb. Below this point the combustion responded too readily to slight changes in draft pressure. Clinker adhering to the ledges accumulated in smaller amounts at the higher rates.

36. *Fuel 5.1006 W*, Table 11. Normally, this fuel contains a very narrow range of intermediate sizes, although as in other well-sized coals, there is always present a proportion of sizes smaller than that of the lower screen. This is caused by the handling dur-

TABLE 11 FUEL 5.1006W

Test No.	Depth of Fuel Bed Inches	Draft Pressure on Fuel Bed Inches of Water	Lb. of Combustible Consumed per sq. ft. of Grate Sur- face per hr.	Horse Power Developed Item 65.1	Horse Power Developed per sq. ft. of Grate Surface	Per cent of Builders Rating Developed Item 67.1	Efficiency of "Boiler and Furnace" Item 72.1	Over-all Efficiency Item 73.1	Per cent of Total Combustible Lost in "Ash and Refuse"	Carbon Dioxide in Flue Gases Per cent
1	2	3	4	5	6	7	8	9	10	11
37	5	0.097	19.55	231.5	6.68	110.2	71.58	70.55	1.47	10.56
38	5	0.088	17.85	211.5	5.54	100.8	71.37	70.10	1.79	11.09
39	6	0.113	18.32	211.5	5.54	100.8	69.64	68.42	1.73	10.79
40	7	0.144	19.03	213.9	5.60	101.9	67.69	66.49	1.78	10.56
41	6	0.146	23.51	270.3	7.08	128.7	69.25	68.08	1.68	11.48
42	5	0.091	15.92	184.6	4.83	88.0	70.13	67.69	2.02	11.27
43	5	0.174	24.45	271.5	7.11	129.3	68.47	67.19	1.82	11.12
44	5	0.230	30.10	321.8	8.42	153.2	65.51	64.24	1.89	10.27

ing shipping. Usually, this proportion of smaller sizes does not exceed 10 per cent for washed coal similar to that from seam 7, when handled directly from the mines, though long storage may increase the amount considerably. This shipment of coal, after about six weeks' storage, was not as uniform as it was desired to have it. On the average, about 15 per cent passed through a $\frac{1}{2}$ -in. sieve, of which amount a little more than one-half was below $\frac{1}{8}$ in. The coal used in tests 42, 43 and 45, taken from the bottom of the bin, showed about 25 per cent through the $\frac{1}{2}$ -in. sieve with 10 to 12 per cent below $\frac{1}{8}$ in.

The first four tests were run at a rate of combustion giving

about normal boiler rating. Three thicknesses of fuel bed were used, the resulting efficiencies being apparently in favor of the 5 - in. fuel bed. Tests 37, 38, 39 and 40 should be compared in that respect, though because of the inequalities of size they are not entirely satisfactory. The results for test 37 do not seem to be normal with respect to the carbon dioxide per cent, but the reason is not shown in the records.

The fuel was of such a nature that the fuel bed was compact and dense in all tests; at times, especially with the 6- and 7-in. thickness, the bed became viscous, and the first serious trouble from clinkering experienced with any of the fuels tested occurred. During a period of two hours in test 40, fluxing of the ash persisted to such an extent that the fuel bed had to be broken up with the slice bar three times.

Test 42 was intended as a check on tests 37 and 38. A normal draft pressure of 0.10 in. was assigned for the test, but for the reason stated above, the resulting rate of combustion was low. Test 41 with a 6-in. fuel bed, but with higher rate of combustion, gave similar though slightly less trouble of the nature experienced during test 40.

A normal draft pressure of 0.18 in. was assigned for test 43. This was increased to 0.20 during the test with an average of 0.194 for the test. A greater increase in the rate of combustion than that obtained for test 41 was expected, but the actual increase was only 4.1 per cent with an increase in the air supply of 7.1 per cent. Thus it appears that the resistance factor for the fuel bed was increased and that the leakage of free air around the grate was greater. Less trouble was experienced in this test from clinkering than in test 41.

In test 44 under a normal draft pressure of 0.26 in., the trouble from incipient clinkering entirely disappeared. The marked drop in the boiler and furnace, and the over-all efficiency in that test is chargeable partly to excess air and low furnace effect and partly to characteristics of the boiler.

Aside from the various occurrences just stated, the furnace observers' report showed that the fuel, except at times of over-hot fuel beds, burned uniformly and required not more than average attention. As tests of the grade of coal, however, the tests are unsatisfactory. The coal of tests 37 and 38 more nearly represents the grade.

The coal burned with a long bright flame, and except in tests 43 and 44, there was no smoke. It is worthy of note that there was no indication of smoke in test 41 although there was less ex-

cess air than for test 43, a fact which indicates a more uniform distribution of the air. In test 43, Ringlemann shade No. 1 was approximated three times. In test 44, there was a faint haze of smoke throughout the test and twice for very short periods a shade corresponding to chart No. 2 was reached. For smoke averages for the tests, see Table 36.

In Fig. 3 and 4, points have been plotted from the results of this set of tests. Smooth curves have been drawn to represent the average course of results, air supply, etc., at different rates

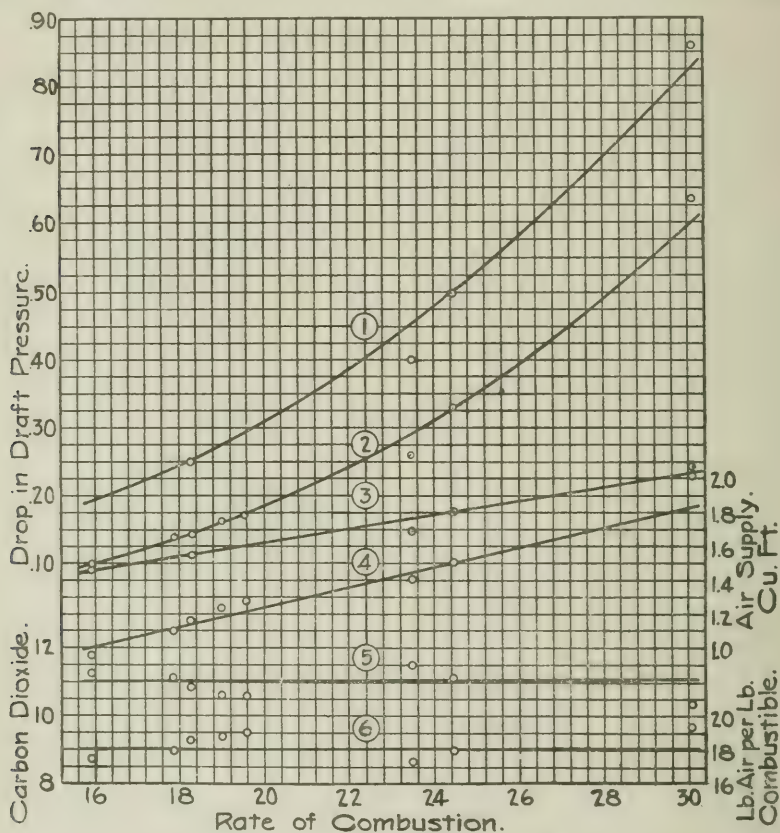


FIG. 3 TESTS OF FUEL 5. 1006 W.

1. Drop in draft pressure through the boiler and fuel bed, inches of water.
2. Drop in draft pressure through boiler, inches of water.
3. Drop in draft pressure through fuel bed, inches of water. 6 in. fuel bed.
4. Cu. ft. of air supplied per sq. ft. of grate surface per sec.
5. Per cent of carbon dioxide in the flue gases.
6. Pounds of air supplied per pound of combustible consumed.

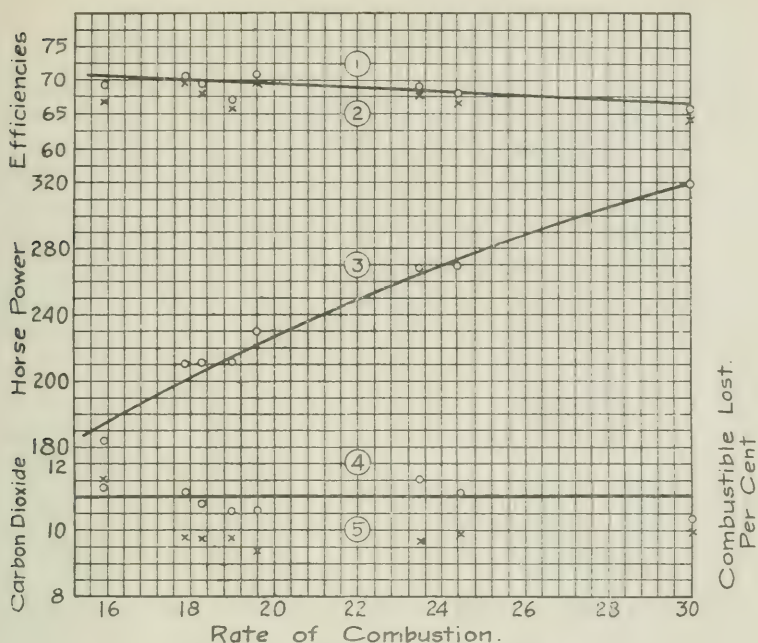


FIG. 4. TESTS OF FUEL 5.1006W

1. Over-all efficiency, E_2 per cent.
2. Over-all efficiency E_1 per cent.
3. Horse-power developed.
4. Per cent of carbon dioxide in the flue gases.
5. Per cent of combustible lost in the "ash and refuse".

of combustion. They are not strictly characteristics of a definite grade, but if each set of points for the individual tests be considered in their variation from the mean curves, much of interest will be found in their general relation to the air supply data and per cent of carbon dioxide.

37. *Fuel 6.0200 W*, Table 12.—Both as to chemical composition and commercial grade, this fuel is similar to the fuel 5.0200W used in the tests of Table 6. At the time of testing, it had been in storage for about 30 days and had dried out somewhat.

Tests 45 and 46 were made with the coal in that condition, the water content being approximately 14 per cent. The tests offer an opportunity of observing the effect of the absence of wetness. In order to take account of the dry condition, the normal draft pressure assigned for the 4-in. bed, test 45, was 0.23 in., 0.29 in. pressure having proved best for the wet coal in test 17. As a result of the dryness, about 40 per cent of the fuel fell through the grate. This was shovelled back into the hopper without wetting. The result was a thin and continually broken fuel bed.

TABLE 12 FUEL 6.0200W

Test No	Depth of Fuel Bed Inches	Draft Pressure on Fuel Bed Inches of Water	Lb. of Combustible Consumed per sq. ft. of Grate Surface per hr.	Horse Power Developed Item 65.1	Horse Power Developed per sq. ft. of Grate Surface	Per cent of Builders Rating Developed Item 67.1	Efficiency of "Boiler and Furnace" Item 72.1	Over-all Efficiency Item 73.1	Per cent of Total Combustible Lost in "Ash and Refuse"	Carbon Dioxide in Flue Gases Per cent
1	2	3	4	5	6	7	8	9	10	11
45	4	0.165	13.35	115.5	3.02	55.0	53.36	48.86	8.39	4.62
46	6	0.313	15.71	131.9	3.45	63.1	52.83	50.44	4.53	4.88
47	6	0.414	16.62	151.4	3.96	72.1	55.86	54.80	1.90	5.53
48	6	0.363	16.81	165.5	4.33	78.8	60.41	58.10	3.78	5.98
49	6	0.303	13.27	121.1	3.17	57.7	55.92	53.02	5.16	5.11
50	5	0.305	15.86	155.2	4.06	73.9	60.56	57.29	5.36	6.04
51	5	0.346	16.28	159.1	4.16	75.8	60.30	57.86	4.02	5.87
52	5	0.364	17.80	175.5	4.59	83.6	60.70	58.60	3.44	6.20

requiring an excessive amount of attention. Poor results generally were shown, and it was with very great difficulty that even fairly good starting and closing conditions for the test were obtained.

Test 46 gave but slightly less trouble. An increased rate of combustion was obtained, but the fuel bed was continually broken and the furnace temperature reduced. These tests are sufficient to show that dryness is not one of the best conditions for fine coal in connection with the chain grate. This is well understood in practice, but perhaps the effect on the efficiency is not so well understood.

During the remainder of the tests of this grade, the coal was sprayed and mixed, the weight of the coal being taken after spraying. The drippings were also sprayed before refring. Spraying the coal reduced the drippings to about 20 per cent of the coal fired.

The results for tests 47 to 52 with some allowance, perhaps 1.5 per cent variation in efficiency, Item 72.1, due to the difficulty of obtaining agreement in starting and closing conditions for the fuel bed, may fairly be considered as characteristic of the fuel and the grate, when given the best possible attention. Reference to Table 40 will show how uniform the conditions of attendance

were. In all of these tests, holes in the fire were checked at their incipency, and the fuel was frequently pushed against the ledge plates.

The furnace observers' report showed the conditions of test 48 to be the most satisfactory for the 6-in. gate opening from the standpoint of operation. For the 5-in. gate opening, the conditions of test 50 gave the least trouble in operation and those of test 52 the most. The rate of combustion and horse-power obtained in test 52 are believed, beyond doubt, to have been the maximum ones obtainable with this particular shipment of coal; the fuel bed was constantly on the point of breaking and considerable care had to be exercised to keep it in good condition.

The dependence of the "boiler and furnace" efficiency upon the temperature of combustion as indicated by the relative percentage of carbon dioxide in the flue gases and the amount of excess air, is plainly shown in these tests. If one will compare the rate of combustion and the quantity of air used in these eight tests, see page 72, an idea will be gained of the uncertainty of the amount of excess air with these fine-sized coals.

Fig. 5 shows the peculiarities of this grade of coal. The maximum rate of combustion, which is between 17 and 18 pounds of combustible per square foot of grate surface per hour, is reached when the volume of air supply is about 1.9 to 2.0 cu. ft. per sq. ft. of grate surface per second. The maximum rate for the 5-in. depth of fuel bed is not shown by the curve, though as stated above, the fuel bed in test 52 in which highest rate was obtained, was continually on the point of breaking even under great care in manipulation. In this test the air was more evenly distributed than in any of the eight tests made. In fact, better distribution of the air supply through the fuel bed and less leakage around the grate seems to be a characteristic of the 5-in. fuel bed for fine sizes. The comparison is shown in the set of curves numbered 2. The relation of the rate of combustion to the draft pressure on the fuel bed, third set of curves, is shown to be linear as long as the fuel bed can be kept in good condition.

In general, it may be said that with especial attention to the operation of the grate and the care of the fuel bed, "boiler and furnace" efficiencies of 56 to 61 per cent and over-all efficiencies from 53 to 59 per cent may be obtained, coincident with 3.2 to

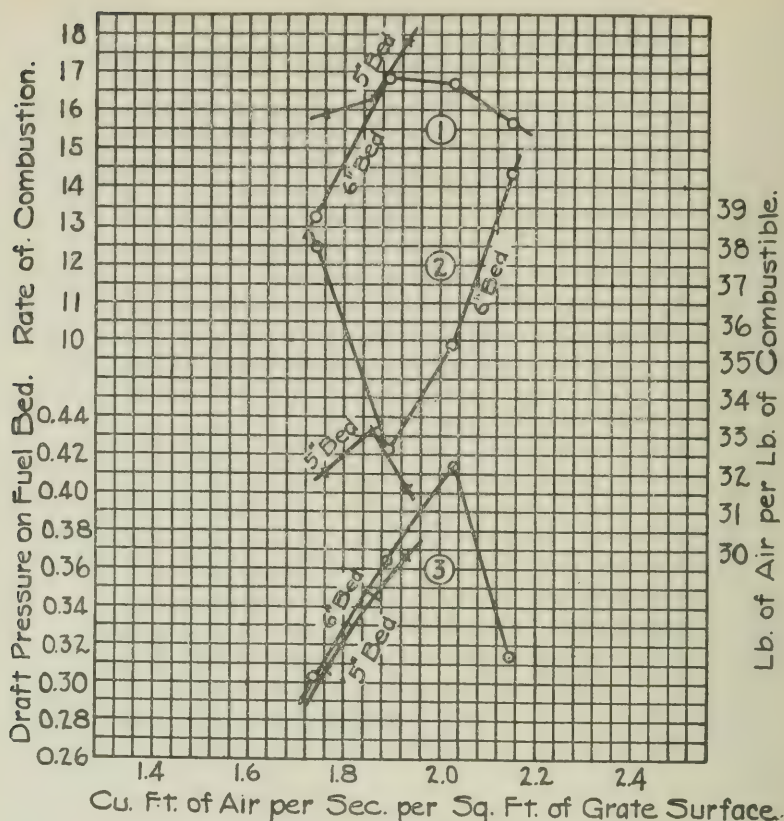


FIG. 5. TESTS OF FUEL 6.0200

1. Rate of combustion, (pounds of combustion consumed per sq. ft. of grate surface per hr).

2. Pounds of air supplied per pound of combustible consumed.

3. Drop in draft pressure through the fuel bed, inches of water.

4.6 horse-power developed per sq. ft. of grate surface per hour.

38. *Fuel 4.0300W*, Table 13—Coal of this grade, passing a $\frac{3}{8}$ -in. screen, is known as washed "duff" at the washery where it is prepared. It is sometimes marketed under that name though it is of larger size than the No. 5 coals of Tables 6 and 12.

Both the sulphur and ash content in this coal were higher than in the No. 5 coal tested. The volatile matter was about 6 per cent greater. One carload of about 24 tons was available, so that in addition to a preliminary test, not reported, but four tests were obtained.

For test 53 a normal draft pressure of 0.34 in. was assigned. The average of the draft pressure reading for the test was 0.336 as shown, and 194.8 H. P.

TABLE 13 FUEL 4.0300W

Test No.	Depth of Fuel Bed Inches	Draft Pressure on Fuel Bed Inches of Water	Lb. of Combustible Consumed per sq. ft. of Grate Sur- face per hr.	Horse Power Developed Item 65.1	Horse Power Developed per sq. ft. of Grate Surface	Per cent of Builders Rating Developed Item 67.1	Efficiency of "Boiler and Furnace" Item 72.1	Over-all Efficiency Item 73.1	Per cent of Total Combustible Lost in "Ash and Refuse"	Carbon Dioxide in Flue Gases Per cent
1	2	3	4	5	6	7	8	9	10	11
53	5	0.339	20.45	196.5	5.15	93.6	59.73	55.88	6.51	6.56
54	5	0.298	16.81	163.8	4.29	78.0	60.98	57.30	6.05	6.16
55	5	0.367	20.71	200.1	5.14	95.3	60.15	56.68	5.79	6.58
56	5	0.381	21.70	210.4	5.51	100.2	60.73	56.76	6.50	6.90

A lower draft pressure was tried for test 54, and resulted in evaporation with no change in efficiency. A normal draft pressure of 0.38 in. was assigned for test No. 55 and 0.40 in. for test No. 56. Considerable trouble was experienced in all of the tests from coal falling through the grate, but less attention was required in keeping the fuel in good condition, than for the No. 5 coal.

In all of the tests, the coal ignited well under the arch and burned more freely and evenly over the grate than the No. 5 coal. The flame was short on account of the large excess of air and no smoke could possibly result. For the same reason no clinker was formed. Test No. 53 required the least attention to the operation of the grate while test No. 56 required the most attention.

It is possible that slightly increased rate of combustion could have been obtained, but at 0.42 inches normal draft pressure there was a serious tendency for holes to form, due to the lifting force of the draft, the light fuel particles dancing about in the same manner as in the case of the No. 5 coal.

The 5-in gate opening was used for this fuel, to agree with the best conditions found for the No. 5 coal.

For the four tests, an average of about 20 per cent of fine coal fell through the grate to the drip plate, and the fuel bed was probably more nearly of a depth represented by a 4-in. fuel bed

of larger-sized coal. Some of the characteristics noted in connection with the fuels of Tables 6 and 12 are noticeable, but the fuel is more even and responds to the draft better. There is at the same time greater uniformity in the relation of the rate of combustion to the horse-power developed. As with the No. 5 coal, the tendency here is toward less excess of air at the maximum rate of combustion, though the fuel bed showed an increased tendency to cake as the excess air was reduced. The results with this fuel are shown graphically in Fig. 6 and 7.

Fig. 6 shows the draft pressure and air supply, plotted against

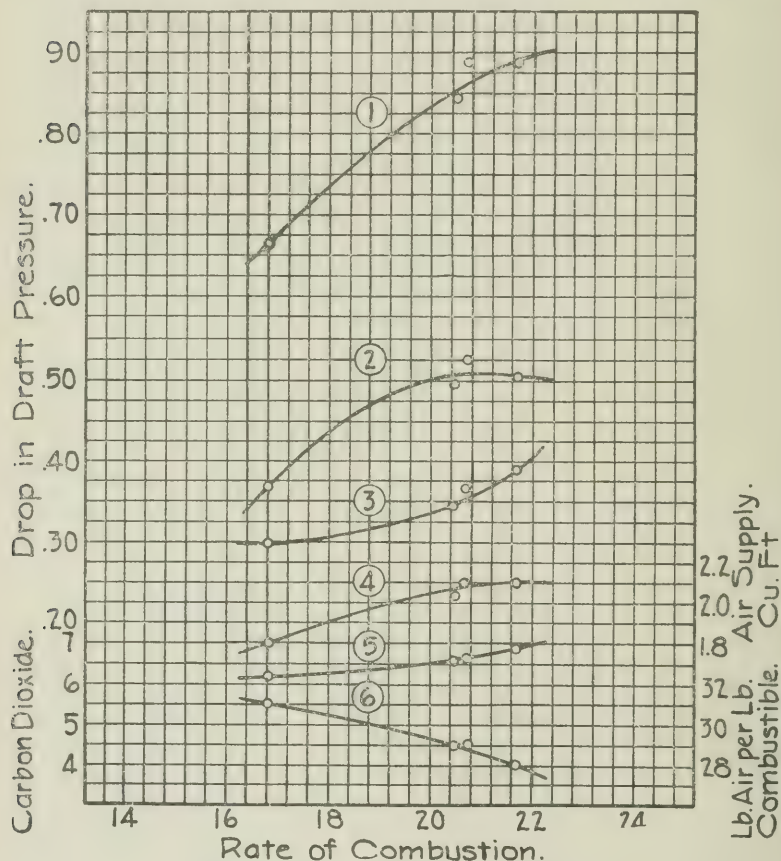


FIG. 6 TESTS OF FUEL 4.0300 W.

1. Drop in draft pressure through the boiler and fuel bed, inches of water
2. Drop in draft pressure through boiler, inches of water.
3. Drop in draft pressure through the fuel bed, inches of water. 5 in. fuel bed.
4. Cu. ft. of air supplied per sq. ft. of grate surface per sec.
5. Per cent of carbon dioxide in the flue gases.
6. Pounds of air supplied per pound of combustible consumed.

the rate of combustion. The curves are characteristic of what may be expected of this fuel. They are not to be considered, however, as showing fixed relations, for, at rates of combustion between 20 to 22, the latter being about the maximum possible rate for the grade experimented with, considerable variation occurs if the fuel bed is not kept in good condition. It will be observed that the rate of combustion does not have the same apparent proportionality to the draft pressure on the fuel bed as in preceding fuels, even under the advantage of increased utilization of the air at the higher rates. Comparing curves 3 and 6, the drop in resistance or friction within the boiler passes (upper portion of curve 2) is due, of course, to the drop in the air supply curve. The deviations of the points for test No. 56 from the mean curves are due to greater leakage.

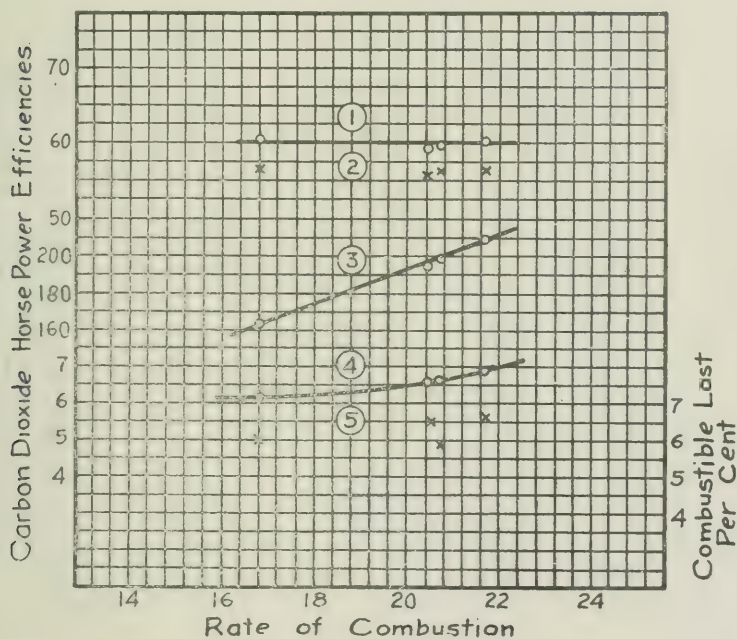


FIG. 7. TESTS OF FUEL 4.0300W

1. "Boiler and furnace" efficiency, E_2 , per cent.
2. Over-all efficiency, E_1 per cent.
3. Horse-power developed.
4. Per cent of carbon dioxide in the flue gases.
5. Per cent of combustible lost in the "ash and refuse".

Fig. 7 shows a slight improvement in evaporation for increasing rates of combustion.

39. *Fuel 4.0703 W*, Table 14.—The two series of tests made with this coal, it is believed, give a means of directly comparing the effect of differences in the furnace control. How closely, how-

TABLE 14 FUEL 4.0703W

Test No.	Depth of Fuel Bed Inches	Draft Pressure on Fuel Bed Inches of Water	Lb. of Combustible Consumed per sq. ft. of Grate Sur- face per hr.	Horse Power Developed Item 65.1	Horse Power Developed per sq. ft. of Grate Surface	Per cent of Builders Rating Developed Item 67.1	Efficiency of "Boiler and Furnace" Item 72.1	Over-all Efficiency Item 73.1	Per cent of Total Combustible Lost in "Ash and Refuse"	Carbon Dioxide in Flue Gases Per cent
1	2	3	4	5	6	7	8	9	10	11
1	6	0.195	25.24	258.9	6.78	123.3	62.78	58.19	7.38	*10.36
2	5	0.157	24.53	264.6	6.93	126.0	65.96	63.96	3.03	* 8.77
3	4	0.116	20.52	214.3	5.61	102.0	63.94	61.34	4.05	*10.26
4	7	0.213	25.79	270.1	7.07	128.6	63.90	61.94	3.02	* 8.86
5	4	0.115	23.90	260.7	6.82	124.2	66.79	64.98	3.78	* 7.82
57	5	0.132	20.71	240.7	6.30	114.6	71.88	69.85	2.90	11.08
58	5	0.118	20.68	241.2	6.31	114.9	70.13	70.40	1.53	11.03
59	5	0.096	15.73	182.9	4.79	87.1	71.43	69.23	3.05	12.50
60	5	0.111	18.27	214.8	5.62	102.3	72.36	70.98	1.94	11.26
61	5	0.137	20.10	230.8	6.04	110.0	70.71	69.21	2.14	10.98
62	5	0.174	25.79	295.2	7.73	140.5	71.14	69.68	2.00	10.93
63	5	0.161	24.55	283.1	7.41	134.8	71.14	69.66	2.07	11.18
64	5	0.058	12.33	146.8	3.84	69.9	72.95	71.65	1.80	12.55

*See page 117.

ever, the two series may be compared in this respect can not be stated. The two sets were made some months apart and no figures are available for the radiation and conduction losses for the earlier tests. See page 53.

In tests 1 to 5, the fuel was not manipulated in any manner and irregularities consequently developed. In the first series, considerable effort was made to keep the fuel bed of standard lengths, but in all of the tests previous to test 26 it was not wholly successful. Otherwise all of the tests were conducted with the same care. Though the unreliability of the gas samples for tests 1 to 5 do not permit an estimation of the amount of excess air nor permit of the estimation of radiation and conduction losses, it is still apparent, from the percentage obtained that the difference in efficiency for the two series was due largely to excess of free air entering the furnace along the ledges and through thin parts of the fuel bed.

The control conditions for tests 57 to 64 differed in no par-

ticular from the standard conditions adopted for tests 21 to 64. As might be expected, this size of fuel from the standpoint of operation is an exceptionally favorable fuel for the chain grate, and with a little care there is no reason why equally good results may not be obtained in regular practice. Some trouble from adhering clinker along the ledges was experienced in each of the tests, due to a high fuel temperature and diminished leakage of cold air. In tests 1 to 5, no clinker was formed along the ledges since the fuel bed was not so hot and the continual stream of cold air between the grate and ledge prevented its formation. This

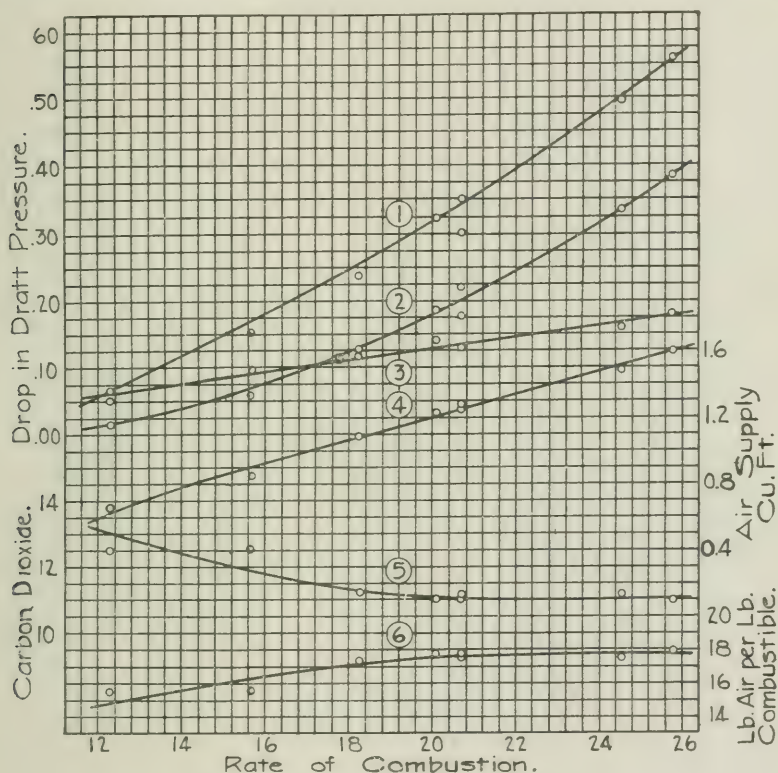


FIG. 8 TESTS OF FUEL 4.0703 W.

1. Drop in draft pressure through the boiler and fuel bed, inches of water.
2. Drop in draft pressure through boiler, inches of water.
3. Drop in draft pressure through the fuel bed, inches of water. 5 in. fuel bed.
4. Cu. ft. of air supplied per sq. ft. of grate surface per sec.
5. Per cent of carbon dioxide in the flue gases.
6. Pounds of air supplied per pound of combustible consumed.

fuel tested the combustion chamber "capacity to consume volatile matter". The flame extended through the combustion chamber and among the tubes in all the tests. Comparing the shade of smoke produced, column 12, Table 36, with the rate of combustion and the amount of air supply, columns 5 and 12, Table 14, it will be seen that the conditions tending to produce smoke depend more upon the proportion of air supplied than upon the rate of combustion. The introduction of a few mixing piers either upon the bridge wall or in the combustion chamber would, of course, result in complete combustion even with considerably reduced excess of air. With the combustion chamber and furnace as they are now, a slightly greater proportion of air is necessary to entirely prevent smoke with this fuel than is needed for the fuel from seam 7 in Williamson county. See Table 11. However, it is not possible to conclude from the evidence of the few tests of these coals available, whether any fundamental difference exists in this respect. The principal point to be noted is the absence

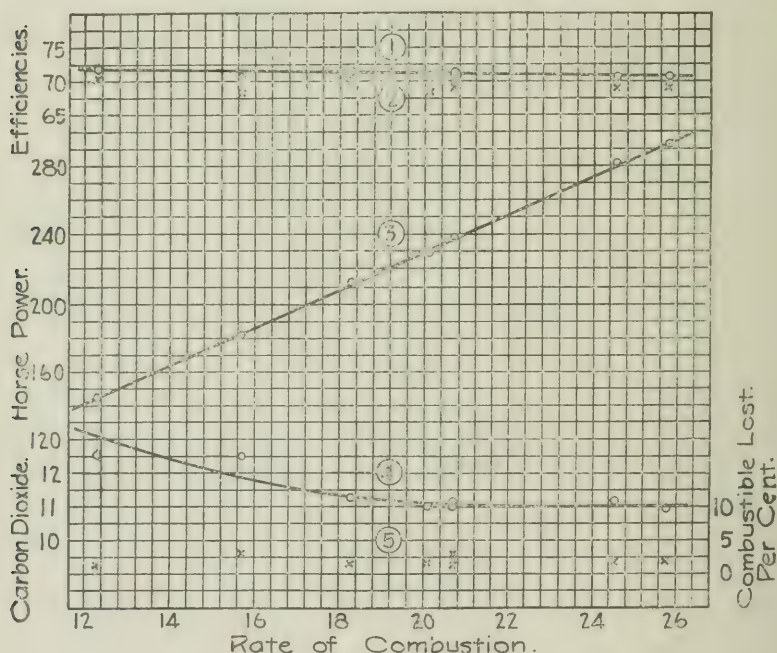


FIG. 9. TEST OF FUEL 4.0703

1. "Boiler and furnace" efficiency, E_2 , per cent.
2. Over-all efficiency, E_1 , per cent.
3. Horse-power developed.
4. Per cent of carbon dioxide in the flue gases.
5. Per cent of combustible lost in the "ash and refuse".

of any pronounced effect of high rates of combustion in producing smoke with a high volatile coal even though the excess air is extremely low.

In Fig. 8, the mean curves show the general relation of the air supply and draft for this fuel (tests 57 to 64) and in Fig. 9 is shown the corresponding evaporative performance.

Aside from the relation shown for this fuel, the curves are of interest from the fact that a wide range of combustion under uniform conditions is shown. The general remarks made in connection with the curves previously noted, apply to these curves as well and much is to be derived from a general study of the relative deviation of the plotted points from the mean curves drawn.

The nearly constant efficiency shown by the curves is of interest. At the low rates of combustion, the excess air was relatively small, as is indicated by the carbon dioxide points and the calculated points of curve 6. Consequently the furnace effect was proportionately higher. That this does not result in an upward flexure of the efficiency curves, is due to increased proportion of the radiation and conduction losses, as will be seen by referring to the values for those losses, Table 16.

VII. COMPARISON OF HEAT VALUES AND ECONOMY

40. Various factors affecting the economic results obtainable with a given coal have been outlined on page 22. The tabulated quantities of Table 16 embrace such of those values as are accessible in the data. For the purpose of uniformity in the fuel unit, the items are based upon the combustible. The derivation of the items is as follows:

Column 3. *Total heat of 1 lb. of combustible, B. t. u. =*
Item 51.

Column 4. *Practical heat value, B. t. u. =* Column 3 less
latent heat of moisture.

Column 5. *Heat delivered, B. t. u. =* Column 4 less
heat lost in carbon of the "ash and refuse."

Column 6. *Furnace effect B. t. u. =* Column 5 $\div$ lb. moist
gases per pound of combustible fed = Column
5 $\div$ (Column 7, Table 24 + Column 3, Table
15)

- Column 7. *Equivalent evaporation from and at 212° per lb. of combustible fed, pounds, compensated for water-back loss = Item 70.1, referred to combustible fed.*
- Column 8. *Service heat value, B. t. u., compensated for water-back loss = Column 7 x 966.*
- Column 9. *Radiation and conduction loss, B. t. u. See p. 56.*
- Column 10. *Service heat value, compensated for radiation and conduction loss. See page 52.*

The heat losses due to latent heat in the moisture from the coal and to the loss of carbon in the ash are shown in Table 15. The items of this table were computed as follows:

- Column 3. *Weight of water per lb. of combustible, pounds = (per cent of moisture referred to combustible ÷ 100) + (per cent of hydrogen in combustible ÷ 100) x 9.*
- Column 4. *Latent heat = Column 3 x 965.8.*
- Column 5. *Per cent of carbon in ash to combustible = (Item 31 x item 44) ÷ (100 — Item 42) See tables 29 and 38 for Item 31, 42 and 44.*
- Column 6. *Heat in carbon lost = Column 5 x 14600.*

41. Reviewing the values set forth in Table 16, it cannot be doubted that the comparative values of two grades of fuels can be apparent only from an actual service test. It will be seen, however, that over-all test results in themselves do not lend themselves to close comparison. In the table are shown approximate values for the furnace effect and the sensible heat delivered per pound of combustible. In the definitions of those quantities, page 18, the radiation and conduction losses from the furnace have been given proper importance. It would likewise be consistent with a possible working hypothesis of steam boiler performance to base such definitions upon quantities of heat only that are delivered to the boiler at temperatures above that of the heating surfaces. However, to give such factors proper weight in the derivation of numerical values more elaboration is required than seems necessary, especially since the cause for variation in the evaporative results may be shown by simpler means. It is believed that this purpose has been sufficiently shown by the two heat quantities in the calculation of which no account has been taken of the radiation and conduction losses, and by way of supplement introducing as a separate item the values for the total radiation and conduction losses, furnace and boiler combined.

TABLE 15 HEAT LOSS DUE TO WATER FROM COAL AND TO CARBON IN ASH.

No.	Laboratory File No.	Water from Coal		Carbon Lost in Ash-pit		No.	Laboratory File No.	Water from Coal		Carbon Lost in Ash-pit	
		Weight per pound	Latent Heat in	Per cent of Combustible	B. t. u. in Carbon Lost			Weight per pound	Latent Heat in	Per cent of Combustible	B. t. u. in Carbon Lost
1	2	3	4	5	6	1	2	3	4	5	6
		Lb.	B. t. u.	P. ct	B. t. u.			Lb.	B. t. u.	P. ct	B. t. u.
1	21-4.0703 W	.716	691	7.38	1077	33	98-7.1610 -	.545	526	2.15	314
2	23- ..	.720	695	3.03	442	34	99- ..	.560	541	2.31	337
3	24- ..	.730	705	4.05	591	35	100- ..	.616	595	2.14	312
4	25- ..	.729	704	3.02	441	36	101- ..	.553	534	2.25	329
5	26- ..	.725	700	3.78	552	37	102-5.1006 W	.601	581	1.47	215
6	30-5.0602 W	.628	606	2.91	425	38	104- ..	.621	600	1.79	281
7	31- ..	.634	612	2.32	339	39	107- ..	.611	590	1.73	253
8	32- ..	.630	609	2.60	379	40	109- ..	.607	586	1.78	264
9	34- ..	.639	617	1.74	257	41	110- ..	.613	592	1.68	245
10	35- ..	.612	591	1.73	252	42	112- ..	.607	586	2.02	295
11	36- ..	.596	576	2.20	322	43	113- ..	.580	560	1.82	266
12	37-5.0200 W	.675	652	7.98	1165	44	114- ..	.576	556	1.89	276
13	39- ..	.655	632	6.12	890	45	115-6.0200 W	.655	633	8.39	1225
14	40- ..	.683	660	5.11	746	46	116- ..	.639	617	4.53	661
15	41- ..	.653	631	10.32	1507	47	117- ..	.765	739	1.90	277
16	42- ..	.709	685	10.27	1506	48	118- ..	.714	690	3.78	552
17	43-4.0700 W	.723	698	4.71	647	49	119- ..	.694	671	5.16	753
18	44- ..	.736	711	3.56	519	50	120- ..	.728	704	5.36	783
19	45- ..	.712	687	6.66	972	51	121- ..	.736	711	4.02	587
20	46- ..	.727	703	3.33	486	52	122- ..	.732	708	3.44	502
21	47-6.0402 W	.599	578	4.35	636	53	124-4.0300 W	.809	782	6.51	950
22	48- ..	.594	574	2.11	307	54	125- ..	.785	759	6.05	883
23	49- ..	.607	587	4.63	675	55	126- ..	.795	768	5.79	845
24	50- ..	.607	587	4.31	630	56	127- ..	.793	766	6.50	949
25	51-5.1610 W	.588	568	5.43	793	57	128-4.0703 W	.697	673	2.90	423
26	52- ..	.628	607	3.85	561	58	129- ..	.799	772	1.53	223
27	53-6.0402 W	.592	572	2.11	308	59	130- ..	.717	693	3.05	445
28	93-5.1610 W	.604	583	1.82	266	60	131- ..	.783	757	1.94	283
29	94- ..	.593	573	2.69	393	61	132- ..	.714	690	2.14	312
30	95- ..	.598	578	2.96	432	62	133- ..	.707	683	2.00	292
31	96-7.1610 -	.613	592	2.45	358	63	134- ..	.739	714	2.07	302
32	97- ..	.555	536	2.30	336	64	135- ..	.740	715	1.80	263

TABLE 16 COMPARISON OF HEAT VALUES AND ECONOMY, BASED ON
1 LB. OF COMBUSTIBLE AS FED.

No.	Laboratory File No.	Total Heat Value	Practical Heat Value	Sensible Heat Delivered	Furnace Effect	Equivalent Evaporation	Service Heat Value	Radiation and Conduction Loss	Service Heat Value, Compensated for Radiation and Conduction Loss
1	2	3	4	5	6	7	8	9	10
		B. t. u.	B. t. u.	B. t. u.	B. t. u.	Lb.	B. t. u.	B. t. u.	B. t. u.
1	21—4.0703 W	14247	13556	12479	.....	8.59	8298	.....	.....
2	23—	14273	13578	13136	.....	9.45	9130	.....	.....
3	24—	14239	13534	12943	.....	9.04	9732	.....	.....
4	25—	14295	13591	12180	.....	9.16	9848	.....	.....
5	26—	14241	13541	12989	.....	9.48	9157	.....	.....
	Average—	14259	13560	12945	.....	9.14	8833	.....	.....
6	30—5.0602 W	14483	13877	13352	.....	9.70	9369	.....	.....
7	31—	14467	13855	13516	.....	9.52	9196	.....	.....
8	32—	14468	13859	13480	.....	9.65	9332	.....	.....
9	34—	14477	13860	13603	.....	9.28	9965	.....	.....
10	35—	14465	13874	13622	.....	9.28	8965	.....	.....
11	36—	14549	13973	13651	.....	9.47	9148	.....	.....
	Average—	14468	13866	13537	.....	9.48	9161	.....	.....
12	37—5.0200 W	14348	13690	12525	.....	7.39	7139	.....	.....
13	39—	14391	13759	12867	.....	7.53	7274	.....	.....
14	40—	14368	13708	12962	.....	7.64	7380	.....	.....
15	41—	14353	13722	12215	.....	7.23	6984	.....	.....
16	42—	14341	13656	12156	.....	7.33	7080	.....	.....
	Average—	14371	13663	12535	.....	7.52	7266	.....	.....
17	43—4.0700 W	14295	13597	12910	.....	9.18	8868	.....	.....
18	44—	14340	13629	13110	.....	9.72	9389	.....	.....
19	45—	14340	13653	12681	.....	9.29	8974	.....	.....
20	46—	14384	13645	13159	.....	9.63	9302	.....	.....
	Average—	14839	13631	12965	.....	9.46	8883	.....	.....
21	47—6.0402 W	14516	13938	13303	.....	10.19	9843	.....	.....
22	48—	14630	14056	13749	.....	10.15	9708	.....	.....
23	49—	14516	13929	13254	.....	10.36	10007	.....	.....
24	50—	14469	13882	13252	.....	10.27	9926	.....	.....
27	53—	14503	13931	13623	.....	9.89	9554	.....	.....
	Average—	14527	13947	13436	.....	10.17	9806	.....	.....
25	51—5.1610 W	14653	14085	13292	.....	9.78	9447	.....	.....
26	52—	14499	13892	13331	.....	9.93	9593	.....	.....
28	93—	14509	13926	13660	599*	9.79	9458	1151*	10609*
29	94—	14472	13899	13506	602*	9.67	9338	1155*	10493*
30	95—	14471	13893	13461	631	9.62	9287	1315	10602
	Average—	14521	13939	13450	631	9.76	9425	... ..	10602

*Not included in average.

TABLE 16 COMPARISON OF HEAT VALUES AND ECONOMY BASED ON
1 LB. OF COMBUSTIBLE AS FED

No.	Laboratory File No.	Total Heat Value	Practical Heat Value	Sensible Heat Delivered	Furnace Effect	Equivalent Evaporation	Service Heat Value	Radiation and Conduction Loss	Service Heat Value Compensated for Radiation and Conduction Loss
1	2	3	4	5	6	7	8	9	10
		B. t. u.	B. t. u.	B. t. u.	B. t. u.	Lb.	B. t. u.	B. t. u.	B. t. u.
31	96—7.1610 —	14573	13981	13623	618	9.71	9384	1355	10739
32	97— ..	14456	13920	13584	613*	9.93	9592	1076*	10668*
33	98— ..	14470	13944	13630	644	9.67	9343	1434	10777
34	99— ..	14548	14007	13670	646	9.72	9394	1347	10741
35	100— ..	14395	13800	13488	629*	9.40*	9086*	1317	10403*
36	101— ..	14436	13902	13573	617*	9.32*	9001*	1224	10225*
	Average—	14480	13792	13594	628	9.76	9428	1335	10752
37	102—5.1006 W	14427	13846	13631	696*	10.54	10179	766	10945*
38	104— ..	14487	13887	13626	738	10.51	10156	743	11099
39	107— ..	14470	13880	13627	718	10.25	9990	1202	11102
40	109— ..	14477	13891	13631	705	9.96	9625	1404	11029
41	110— ..	14487	13895	13650	761	10.21	9863	1084	10947
42	112— ..	14425	13859	13545	730	10.11	9764	1534	11298
43	113— ..	14145	13585	13319	722	9.81	9503*	1023	10526*
44	114— ..	14240	13684	13408	675*	9.47*	9148*	849	9997*
	Average—	14395	13813	13555	729	10.20	9915	1076	11095
45	115—6.0200 W	14145	13512	12287	314*	7.15*	6911*	652	7563*
46	116— ..	13920	13303	12642	324*	7.27*	7021*	903	7924*
47	117— ..	14233	13494	13217	366	8.07	7800	924	8724
48	118— ..	14229	13539	12987	401	8.56	8267	536	8803
49	119— ..	14229	13558	12805	346	7.81	7545	831	8276
50	120— ..	14087	13383	12600	400	7.32	7072	656	7728
51	121— ..	14133	13422	12835	360	7.47	8150	595	8775
52	122— ..	14166	13458	12956	411	8.59	8302	480	8782
	Average—	14143	13458	12791	386	7.97	7861	697	8515
53	124—4.0300 W	14031	13249	12299	438	8.12	7841	605	8446
54	125— ..	13948	13190	12307	405	8.27	7992	442	8434
55	126— ..	14065	13237	12392	431	8.22	7939	595	8534
56	127— ..	13954	13188	12239	450	8.09	7819	586	8405
	Average—	13984	13216	12309	431	8.23	7898	557	8455
57	128—4.0703 W	14090	13417	12994	722	10.19	9843	637	10480
58	129— ..	14210	13438	13215	710	10.36	10003	524	10527
59	130— ..	14212	13419	13074	805*	10.19*	9839*	1296	11135*
60	131— ..	14171	13414	13131	725	10.41	10058	750	10808
61	132— ..	14161	13471	13159	714	10.15	9805	867	10672
62	133— ..	14045	13362	13070	705	10.13*	9768*	485	10253*
63	134— ..	14133	13419	13117	721	10.19*	9846*	504	10350*
64	135— ..	14229	13514	13251	817*	10.55*	10193*	1303	11496*
	Average—	14156	13444	13126	716	10.28	9927	796	10622

*Not included in average.

42. Over-all evaporative results in tests of fuels may be compared quantitatively only when the imposed operating conditions of the experiment are carefully taken into account, but the comparison will hold only when the experiments themselves have been made without variation due to losses from radiation and conduction. The present studies clearly show that it is impossible to eliminate such variations, and that some means of correction for the radiation and conduction losses must always be applied. In general, it may be stated that the evaporation depends upon

- (1) the heat content of the gas;
- (2) the heat delivered per pound of fuel;
- (3) the boiler characteristics;
- (4) radiation and conduction losses.

43. The values for the radiation and conduction losses for those tests (tests 30 to 64) for which there are data suitable for calculating a satisfactory heat balance, are given in column 9, Table 16. These values are the "unaccounted-for loss" items obtained in heat balances as usually computed. This item, which is obtained by subtracting the total heat measured from the total heat supplied, also represents the variations due to the balance between positive and negative errors of experiment. What weight the latter represents in the figures, cannot be ascertained. It seems reasonable to believe, however, that with the exception of those tests that have been questioned in the table, the sum of these errors does not exceed 1 per cent.

44. Comparison of the variation between the radiation and conduction losses shows the extent to which the service heat values have been affected. It should be especially noted that those tests conducted in the early spring are placed at the greatest disadvantage, e. g., fuels 7.1610—and 5.1610 W. In fixing upon a method of correction for these losses, an endeavor was made to arrive at some satisfactory means of correction for the variations only, such that the resulting corrected values would represent magnitudes obtainable by direct experiment under uniform conditions, but the possibility of such a course has been precluded for the want of a satisfactory datum of reference. The involved nature of the problem will be apparent if one reviews the various

factors that contribute to the magnitude of such losses.

However, for purposes of comparison, it is not essential that the values should numerically represent obtainable ones, and a compensation has been made in column 10 by adding the heat loss of column 9 directly to the obtained figures for the service heat value. This procedure, though somewhat arbitrary, represents the best possible information, since the values approximate those that would have obtained had the heat lost by radiation and conduction from the furnace remained in the gases; further, they eliminate any variations due to radiation and conduction from the boiler, and at the same time those that may have been introduced by errors in the coal or in the water items. This method of compensation is adopted on the theory that heat imparted to the gases above the temperature of the boiler heating surface is absorbed at very high efficiency.*

Since this efficiency, it is known, is not perfect, the figures thus obtained do not strictly represent a function embracing the heat quantities tabulated. Considering these as relative figures only, there appears no reason why, imposed conditions of operation being equal, they should not be comparable within 1 per cent total variation, whereas the over-all results, as is usual with such values, call for considerable latitude of judgment.

45. In bringing results for all of the tests together in Table 16, it is not intended to imply that the results for all tests are strictly comparable. They are brought together to give a survey of the results not afforded by other tables. Tests 1 to 20, as elsewhere pointed out, were made under different conditions of furnace control than were those of succeeding tests.

Values for the radiation and conduction losses were not obtained for tests 1 to 27, and hence a proper presentation of those tests is difficult. At the outset of the tests, it was expected that inasmuch as the boiler was housed in an independently heated building, variations from that source would be small. That between tests run some weeks apart the variation would be as shown was, however, not expected. Upon the disclosure of the conditions, it was at first thought that the results of tests 1 to 27 should be rejected. Careful analysis of those results, however, does not disclose marked variations within any one fuel series which can

*For the major number of tests made at St. Louis by the U. S. Geol. Survey, it was shown that between 80 and 87 per cent of the heat in the gases above steam temperature was absorbed. "A Study of Four Hundred Steaming tests" Bul. 325, U. S. G. S., p. 147.

not be approximately accounted for by other occurrences on record. For this reason and because their value for the other objects of the investigation has not been affected, they have been included in the report. Equal reliability of the results of tests 1 to 27 as representing the conditions that existed is not questioned. The value of these tests as a basis for comparison of the relation of grade to economy is affected, however, for the reasons given. If the tests serve no further purpose in the present connection than to emphasize the importance of reliable flue gas data in experimental boiler and furnace work, the prominence given them will not be without value.

46. The averages shown for the results of each fuel series give a hasty review of the results. In making them, values for tests run at relatively high or low horse-power or rates of combustion have been excluded, as have likewise certain other values which preceding analyses have shown to be in question.

For purposes of more accurate comparison, these averages are supplemented by Table 17. The tests compared therein with one exception, test 52, fuel 6.0200 W, represent tests at approximately 210 H. P., and are tests selected especially because of their uniform furnace operation and conditions. For fuel 6.0200 W, 210 H. P., was not obtainable. The items of the table are compiled from Table 16. The ratios at the lower part of the table are taken with respect to the items for test 60, fuel 4.0703 W.

47. *Size of grade and air proportion.*—The relation of the comparable values of column 8, Table 17, to the various heat quantities has been discussed at length. It is also important to look upon the variation of value from the relationship of size and air proportion. Keeping in mind the minor modifications introduced by variations in the heat delivered per pound of fuel, the following is of interest.

48. Air enters the furnace through the active fuel bed and through leakage points outside of the fuel bed. With any constant draft pressure, the relative proportion of the total air supply entering through each source of entrance is proportional to the separate resistances of these sources. The resistance at entrance points outside the fuel bed is practically constant, but the resistance of the fuel bed (neglecting other modifying factors for the present) depends upon the sizes of the interstices between the coal particles. Thus the leakage relative to the total air

TABLE 17 HEAT VALUES AND ECONOMY—BASED ON COMBUSTIBLE AS FUD (SELECTED TESTS)

	No.	Fuel	Total Heat Value	Practical Heat Value	Sensible Heat Delivered	Furnace Effect	Service Heat Value, Compensated for Radiation and Conduction Losses
1	2	3	4	5	6	7	8
Heat Quantities	30	5.1610 W	14471	13893	13461	631	10602
	31	7.1610 —	14456	13920	13584	613	10739
	38	5.1006 W	14487	13887	13626	738	11099
	52	6.0200 W	14166	13458	12956	411	8782
	56	4.0300 W	13954	13188	12239	450	8405
	60	4.0703 W	14171	13414	13131	725	10808
Ratios	30	5.1610 W	1.021	1.036	1.035	0.870	0.981
	31	7.1610 —	1.020	1.038	1.035	0.846	0.994
	38	5.1006 W	1.022	1.036	1.038	1.018	1.039
	52	6.0200 W	1.000	1.004	0.987	0.567	0.813
	56	4.0300 W	0.984	0.983	0.932	0.621	0.778
	60	4.0703 W	1.000	1.000	1.000	1.000	1.000

increases as the compactness of the fuel bed increases, and in increasing proportion as it becomes necessary to increase further the draft pressure to give the same rate of combustion or horse-power.

49. The size of the interstices between the coal particles increases with the size of the coal particles, consequently with large grades of uniform coal a large proportion of the total air passes through the fuel bed. As the interstices are further increased, however, a condition is reached where a part of the air may pass through the fuel bed without coming into contact with either gaseous or solid combustible. Thus the fuel bed itself becomes an entrance for excess air. Between the large size, therefore, with excess air entering the furnace through the fuel bed, and perhaps by leakage as well, (some excess is needed with volatile coals for the combustion of the gasified hydrocarbons), and fine sizes with a large proportion of leakage, a size will be found for which a minimum excess occurs. This general consideration would apply more strictly to a non-clinkering and free-burning

coal, except for very fine sizes. Clinkering, caking, and with fine sizes, the formation of craters in the fuel bed, modify the conditions.

50. Ash—It is held, hypothetically, that the presence of ash particles in the fuel bed decreases the chance of the air coming in contact with the solid coal substance, and, depth of fuel bed constant, that the proportion of excess air should increase with increased percentage of ash. Analyses of 286 tests at St. Louis*, however, do not show that this is true in connection with the *plain* grate for ash percentages below 16 per cent, but it was shown that clinkering of the ash is of more serious consequence because of obstruction of the grate. The extent and seriousness of clinkering depend upon the fluxing properties of the ash, the temperature of the fuel bed and the quantity of ash present. Parenthetically, it should be said that the mere presence of ash in quantity does not induce clinkering; in fact, ash which fuses in a hot fuel bed may, by its presence in large amounts, operate to prevent clinkering by inducing excess air cooling of the fuel bed and furnace.

51. Tests with the chain grate stoker, by Mr. W. L. Abbott†, to determine the effect of varying percentages of ashpit refuse added to No. 4 washed coal, show the following results for percentages of ash below 25 per cent.

TABLE 18

Per cent of Ash in Dry Coal	Efficiency
9	59.0
16	57.0
20	61.5
24	56.0
24	57.0

For percentages of ash above 30 per cent, Mr. Abbott's results varied widely, as might be expected. Results for the lower percentages show no greater variations than are usual to over-all results.

52. The percentage of ash for the tests of Table 17 range from 9 to 16 per cent, dry coal basis, and it appears from the results just quoted that except for tests of fuel 5.1006 W, in which serious clinkering occurred, no important variations are to be ascribed to ash, but that the excess air quantities, (see p. 80), under the test conditions, are to be considered as characteristics of the grade

*Bul. U. S. G. S. 190, p. 39.

†Jour. Wester Soc. Engrs. Vol. 11, p. 529.

sizes. This would in fact be true under any consideration since the percentages of ash in washed grades have a close relation to the grade size.

In the paper quoted above, Mr. Abbott has shown a similar and remarkable relationship for specially prepared *unwashed* sizes based, however, upon size and *efficiency*.

VIII. EFFECT OF DIFFERENT THICKNESSES OF FUEL BED

53. In connection with the detailed statement concerning results set forth in Tables 5 to 14, a cursory examination of the effect of different thicknesses of fuel bed has been made. It is intended here to summarize the general conclusions in that respect presented by the data. Aside from a general contribution to the data on each grade, two points of interest in respect to the thickness of fuel bed have been under investigation.

(a) The first of these was to determine whether any difference in the amount of combustible matter in the ash-pit refuse would result for different thicknesses of fuel bed.

(b) The second point of interest relates to the determination of whether or not a different economy would result for different thicknesses.

54. *Loss of Fuel in the "Ash and Refuse"*.—Relative to the first question, it was thought that thick fuel beds, with their higher interior temperature and consequent higher temperature of the layer of ash beneath, together with the proportionately greater quantity of air which must necessarily pass through each unit area of the ash bed, would result in smaller ash-pit loss; that is, according to the accepted notion of combustion and of the protecting effect of ash in quantity, the chances of air coming into contact with the imbedded fuel particles are in proportion to the product of the rate of air flow and the time that the ash remains upon the grate.

55. In Table 19, the averages of the available data for each thickness of fuel bed are given for the several grades. Compar-

TABLE 19 RELATION OF LOSS OF FUEL IN THE "ASH AND REFUSE" TO THE THICKNESS OF THE FUEL BED

Thickness of the Fuel Bed, Inches	Loss of Fuel, per cent of Total Combustible									
	Fuel 5.0602 W	Fuel 5.0200 W	Fuel 4.0700 W	Fuel 6.0402 W	Fuel 5.1610 W	Fuel 7.1610 —	Fuel 5.1008 W*	Fuel 6.0200 W	Fuel 4.0300 W	Fuel 4.0703 W
1	2	3	4	5	6	7	8	9	10	11
4	2.91	10.29	6.66	4.31	.....	.....	.....	8.39	.....	.....
5	2.60	7.98	4.13	4.63	2.96	2.45	1.76	4.27	6.21	2.18
6	2.20	5.61	3.33	3.26	2.69b	2.25	1.78	3.84	.....	.....
7	1.73	.....	.....	3.01	1.82	2.15	1.78	.....	.....	.....

ing these results with the conditions of fuel bed area, (columns 3, 4, 5 and 6, Table 40), it will be seen that the variations in the latter had a minor effect upon the ash-pit loss. Comparing the ash-pit loss with the grate travel (column 12, Table 40), it appears that the latter *per se*, is not the factor in determining the percentage of loss. This is verified by the fact that the slight variations in the loss for the same grade and the same thickness of fuel bed show no relation to the difference in rates of combustion.

56. The explanation of the variation of loss due to difference in thickness for one grade, it is believed, agrees with the premise which led to the carrying out of the experiments.

Inspection of the difference in loss with different grades for the same thickness of fuel bed shows that there is a general coincidence between increased loss and the increased ash in the coal, and likewise the amount of excess air used in burning the coal, factors which affect the depth and the temperature of the ash layer. That these two factors determine the difference between losses for different grades, when the variations due to irregularities of operation are minimized, seems reasonable, but the effects can not be shown separately in the data available.

57. *Effect of Thickness of Fuel Bed upon Economy.*—Coke, just as anthracite coal, requires a moderately thick fuel bed in order

b. Tests 25 and 26 not included.

that the air supplied through the bed may be satisfactorily utilized. For bituminous coal, on the other hand, because of the volatile matter gasified in the voids between the coal particles, a much thinner fuel bed suffices. In the combustion process upon mechanical stoker grates, conditions are peculiar; at the feed end of the grate bituminous coal is under combustion with a deficiency of air, while over a greater or less portion of the grate, coke is under combustion with a thin fuel bed, and therefore with the possibility (depending upon the size of the fuel and the degree of caking which has occurred) of a greater or less excess of air. Thus the relative depths of fuel along the grate from the feed gate to the ashpit are the reverse of what would be considered good practice in hand firing. It has usually been assumed that thicker fuel beds for the chain grate stoker result in less excess of air and better economy. To what extent this would affect the choice of thickness of fuel bed in the comparison to be made of grades, became naturally a question for investigation.

58. Two series of experiments with the chain grate by W. L. Abbott*, one with No. 5 washed coal at a depth of fuel bed from 4.5 to 8.5 inches, and one with washed screenings at depths from 4 to 12 inches, resulted in minor variations only in the efficiency E₂. In explaining his results, Mr. Abbott concluded that "under these conditions, a thin fire increases the loss due to excess of air, but decreases that due to smoke and incomplete combustion. On the other hand, a thick fire reduces the excess of air, but increases the smoke and escaping combustible gas." The experiments were made in connection with a Babcock and Wilcox boiler; and to the length of the vertical pass, 14 tubes high, Mr. Abbott speculatively attributed some of the influence toward constancy of results.

59. With the equipment used in the experiments of the present paper, no smoke results under proper operation at any thickness of fuel bed, so that previous opinion seemed to confirm the expectation of a difference in results under such conditions. In outlining the experiments, thicknesses of fuel bed to be used were confined to those usual in practice. In the first few experiments, it became apparent that any differences in results due to different thicknesses of fuel bed were small, and it appeared extremely doubtful whether they could be shown upon the basis of over-all

* Jour. Western Soc. of Engineers, Vol. 11 p. 529.

results. The results up to test 27, due to the failure to obtain satisfactory flue gas samples, gave no indication as to how much the resulting efficiencies might be affected by radiation losses; consequently, tests 28 to 34, 37 to 40 and 45 to 52, were intended to be suitable for closer comparison.

60. All tests intended for comparison in this respect were to be run with a developed horse-power of as nearly boiler rating as possible; but in order that they might be consistent with the general plan to maintain as nearly an even rate of combustion as possible throughout any one test, and thus be available for other comparisons, they vary slightly above or below, depending largely upon the closeness with which the draft requirements were pre-estimated. For the smaller sizes of fuel, however, the problem as previously noted resolved itself into a determination of the most favorable conditions for maximum results and the results obtained are generally not only below 210 horse-power but themselves vary considerably.

Other desirable features in order that the results should be free from modifications in the air supply not due to variation in the thickness of fuel bed, are:

- (a) Uniformity of the fuel.
- (b) Uniform area of the fuel bed.
- (c) Uniform conditions of the fuel bed.
- (d) Uniformity as to clinkering or caking.
- (e) Leakage influenced normally in respect to draft pressure.

61. Taking these desiderata into account, and guided by the exacting criticisms of the data that have been made in connection with the discussions of Table 5 to 14, a number of tests have been rejected. Those which conform more closely are tabulated in Tables 20 and 21. The following tests have been used in these tables:

- Fuel 5.0200W,—tests 12, 13, 14, 15 and 16.
- Fuel 4.0700W,—tests 17, 18, 19 and 20.
- Fuel 6.0402W,—tests 21, 22, 23 and 24.
- Fuel 5.1610W,—tests 28, 29 and 30.
- Fuel 7.1610—,—tests 31, 33 and 34.
- Fuel 6.0200W,—tests 48, 50 and 51.
- Fuel 5.1006W,—tests 38, 39 and 40.

TABLE 20 RELATION OF EFFICIENCY TO THE THICKNESS OF THE FUEL BED

Thickness of Fuel Bed, inches	Fuel 5.0200 W			Fuel 4.0700 W			Fuel 6.0402 W			Fuel 5.1610 W		
	Over-all Efficiency, E_1	Per cent of Total Combustible Lost in the Ash and Refuse	"Boiler and Furnace" Efficiency, E_2	Over-all Efficiency, E_1	Per cent of Total Combustible Lost in the Ash and Refuse	"Boiler and Furnace" Efficiency, E_2	Over-all Efficiency, E_1	Per cent of Total Combustible Lost in the Ash and Refuse	"Boiler and Furnace" Efficiency, E_2	Over-all Efficiency, E_1	Per cent of Total Combustible Lost in the Ash and Refuse	"Boiler and Furnace" Efficiency, E_2
1	2	3	4	5	6	7	8	9	10	11	12	13
4	49.56	10.29	55.32	64.69	6.66	67.04	68.56	4.31	71.65			
5	49.76	7.98	54.08	63.82	4.13	66.55	68.90	4.63	72.24	64.18	2.96	66.14
6	51.55	5.61	54.65	64.68	3.33	66.80	67.84	4.35	70.92	64.52	2.69	66.28
7	.....	.....	.....	.....	.....	.....	66.98	3.01	68.46	65.19	1.82	66.38

TABLE 21 RELATION OF EFFICIENCY TO THE THICKNESS OF THE FUEL BED

Thickness of the Fuel Bed, inches	Fuel 7.1610—				Fuel 6.0200 W				Fuel 5.1006 W			
	Over-all Efficiency, E_1	Per cent of Total Combustible Lost in the Ash and Refuse	"Boiler and Furnace" Efficiency, E_2	Furnace Effect	Over-all Efficiency, E_1	Per cent of Total Combustible Lost in the Ash and Refuse	"Boiler and Furnace" Efficiency, E_2	Furnace Effect	Over-all Efficiency, E_1	Per cent of Total Combustible Lost in the Ash and Refuse	"Boiler and Furnace" Efficiency, E_2	Furnace Effect
1	2	3	4	5	6	7	8	9	10	11	12	13
5	64.40	2.45	65.90	618	57.57	4.69	60.43	395	70.10	1.79	71.37	738
6	64.58	2.31	66.13	646	58.10	3.78	60.41	401	68.42	1.73	69.64	718
7	64.56	2.15	65.97	644	.....	.....	.....	...	66.49	1.78	67.69	705

62. The tests of fuel 5.1006W were affected by increased clinkering with increased thickness of the fuel bed. This feature seemed to be characteristic of this fuel. However, the three tests need not be given the same weight as the other tests selected. The tests of fuel 5.0602W, Table 22, may be usefully reviewed in this connection, for although the fuel bed areas were irregular as compared with the conditions for the tests of Tables 20 and 21, and although no attention was given to diminish sources of air leakage (the general efficiency was uniformly low on this account), it will be seen that the results for the different thicknesses of fuel bed are parallel to those of the closely similar grade 6.0402W. The lesser values for the 6- and 7-in. beds, as previously stated, page 25, are partly attributable to irregularity of the grate performance.

TABLE 22 FUEL 5.0602 W

Thickness of Fuel Bed inches	Over-all Efficiency E_1 Item 73.1	Per cent of Total Combustible Lost in the Ash and Refuse	"Boiler and Furnace" Efficiency, E_2 Item 72.1
4	64.72	2.91	66.66
5	64.42	2.60	66.16
6	61.91	2.20	64.38
7	62.00	1.73	63.09

63. The values for the furnace effect in Table 21, columns 5, 9 and 13, eliminate the variations due to radiation losses for those tests and serve as a qualitative check on the direction of the variations. For the fuel 7.1610—, the figures indicate that a decreased excess air resulted with thickened fuel bed. No difference is shown for the 5- and 6-in. fuel beds of fuel 6.0200W. For the fuel 5.1006W an increase in the excess air with thickened fuel bed is shown. Column 6, Table 24, gives directly the excess air figures for these tests. Inspection of the results for the different fuels shows, except for fuels 5.1006W and 5.0602W, a variation in the over-all efficiency E_1 of less than 2 per cent for the range of thickness tried.

64. The tendency toward decrease in ashpit loss as the fuel bed is thickened, has already been noted. Decrease in ashpit loss has its proportionate effect upon the over-all efficiency, so that the effect of different thicknesses upon the utilization of the air supply would be better shown by the efficiency E_2 .

65. The effect of radiation and conduction losses for the tests of Table 20 and for the fuel 5.0602W cannot be shown. For those tests for which values for the radiation and conduction losses have been obtained, Table 16, it will be noted that the variations in those losses are not great for tests of one grade which were run at approximately the same rate of combustion, though exception must be made for the tests of fuel 5.1006W in which various irregularities occurred. These facts may be noted by inspection and it will be seen that the conclusions based upon the selected data above, it so happens, are not modified.

66. The reason E₂ fails to show a definite increase with increase in the thickness of the fuel bed, must be explained by the facts that leakage of air otherwise than through the fuel bed proper is proportional to the draft pressure, while the total rate of air flow is approximately constant under the conditions. Compare column 6, Table 24, for the tests analyzed. Stated in other words, the resistance of the natural leakage points is more nearly constant than is the fuel bed resistance which increases with increased thickness of the fuel bed.

67. Since the variation in results due to different thicknesses of fuel bed is only of such magnitude as may result from slight irregularities in furnace control, and is smaller than those due to possible irregularities under ordinary operation, it is evident that the selection of fuel bed depth should be governed by the attention required for uniform results. The test records from the furnace observer's report show that a five-inch fuel bed is most satisfactory for the fuels below the size $1\frac{3}{4}$ to 1; for the latter size, a 6-in. fuel bed was preferred.

IX. RELATION OF GRADE TO THE RATE OF COMBUSTION AND HORSE POWER

68. In the various tabulations given elsewhere in the report, the rates of combustion and horse-power obtained as results of the experiments are included. With the exception of those grades that show a maximum rate within the limits of the experiments, there is no doubt that the grades tested should give any range in rates of combustion desirable for stationary practice, provided suitable draft capacity is available.

69. Very satisfactory means are at hand for a comparison of the economic values of fuels, and it seems that some means of comparing rate of combustion and horse-power would be of commensurate usefulness. Obviously, such a comparison must give due consideration to draft conditions, and in any steam plant it would be most direct to compare fuels under the draft conditions prevailing. Mr. Abbott's tests show an interesting comparison of power obtained with various fuels under restricted draft conditions.

70. Numerous factors modify draft conditions, such as height and capacity of chimney, capacity of the draft fan, difference in the friction within the boilers, the capacity of the lateral flues, the number of furnaces served by each flue, the rate at which they are driven, etc. To consider all of these factors makes the question of draft conditions an extremely complicated one, so much so that all efforts of engineers to formulate a rational treatment of the subject has been unsuccessful. Empirical and approximate formulas supplemented by the judgment of the designer, are relied upon in designing draft systems, so that until more rational methods are devised, the results obtained under one set of plant conditions naturally must be looked upon as restricted in their application.

71. A satisfactory comparison of rates of combustion should eliminate all modifying factors except those of the furnace and the fuel, and the comparative figures obtained should be applicable to any condition of draft within the range of requirements of the fuels in question.

72. It is sometimes thought that a fundamental basis for comparing rates of combustion should be found in some arbitrarily chosen draft pressure, but though the knowledge of draft pressure requirements for each separate grade is invaluable for proper furnace control, a comparison of the draft pressure requirements over an extended range for several grades will show that as many relative values for rates of combustion may be selected as there are possibilities of choosing a basic draft pressure value. This is true for a comparison upon the basis of the drop in draft pressure, whether the drop for the fuel bed, or the boiler, or the two combined is considered. These complications are, of course, due to the fact that the draft pressure is never a measure of the quantity of air supply except under very special conditions.

It seems, therefore, that a logical comparison must necessarily be based upon factors that are fundamental in the actual combustion of the fuel and not upon incidental factors.

73. In the comparisons made below, the principles set forth on page 18 are made use of. It is evident that at a constant rate of air supply, the "ratio of the air used to the air supplied" is equal to the ratio (at constant rate of air supply) of the weight of fuel consumed, to the weight of fuel which it is possible to consume under complete utilization of the air supplied.

This ratio is termed here the *relative rate of combustion*.

$$\begin{aligned}\text{The relative rate} &= \frac{\text{Rate of combustion obtained}}{\text{Maximum possible rate}} \times 100 \\ &= \frac{\text{air used per pound of fuel}}{\text{air supplied per pound of fuel}} \times 100\end{aligned}$$

74. *Comparison of Rates of Combustion.* The following comparisons are based upon the principles just outlined. The values for the relative rate are those given in column 5, Table 24; the values for the volume of air supplied per second are those of column 6 of the same table. A review of the comparisons made under three (3) below will show that it is not essential that the figures for the volume of air supply exactly agree.

(1) A comparison of the larger grades upon the basis of 1.5 cu. ft. of air per sq. ft. of grate surface per second is as follows:

Test No.	Fuel	Relative Rate	Rate of Combustion (Test Data)
30	5.1610 W	55.0	19.35
34	7.1610---	56.3	21.02
43	5.1006 W	63.8	24.45
63	4.0703 W	64.7	24.55

(2) Comparison of three smaller grades and the fuel 7.1610— at 2 cu. ft. of air supplied per second shows:

Test No.	Fuel	Relative Rate	Rate of Combustion (Test Data)
36	7.1610---	54.2	26.05
44	5.1006 W	58.5	30.10
56	4.0300 W	42.4	21.70
47	4.0200 W	33.2	16.62

(3) Comparisons within individual grades with respect to relative rates of combustion with various rates of air supply show:

Fuel 4.0300W

Test No.	Air Supply	Relative Rate	Rate of Combustion (Test Data)
54	1.808	37.0	16.81
53	2.036	39.3	20.45
55	2.093	39.4	20.71
56	2.095	42.4	21.70

Fuel 6.0200W

49	1.735	30.6	13.27
50	1.759	36.0	15.86
51	1.860	35.4	16.28
48	1.888	35.1	16.81
a45	1.919	28.2	13.35
52	1.933	37.2	17.80
b47	2.026	33.2	16.62
a46	2.154	29.2	15.71

a. Very dry fuel.

b. Very wet fuel.

Fuel 5.1610W

30	1.42	55.0	19.61
29	1.46 ¹	52.3 ¹	19.06
28	1.48 ¹	52.4 ¹	19.35

NOTE 1. Gas sample diluted by leak.

Fuel 7.1610—

31	1.408	55.8	19.32
32	1.423 ²	54.0 ²	18.90
33	1.466	56.2	20.44
34	1.507	56.3	21.02
35	1.664	56.9	23.40
36	1.943	54.2	26.05

NOTE 2. Gas sample diluted by leak.

Fuel 5.1006W

42	0.96	64.6	15.92
38	1.102	65.8	17.88
39	1.166	65.1	18.32
40	1.233 ³	63.0 ³	19.03
41	1.396	65.9	23.51
43	1.503	63.8	24.45
44	1.997	58.5	30.10

NOTE 3. Fuel bed clinkered badly.

Fuel 4.0703W

64	0.655	72.5	12.33
59	0.847	71.6	15.73
60	1.088	64.8	18.27
61	1.230	63.9	20.10
57	1.250	65.2	20.71
58	1.266	64.4	20.68
63	1.480	64.7	24.55
62	1.589	63.1	25.79

Inspection of these tabulations shows for the larger grades a tendency toward decreasing relative rate as the rate of air supply and the rate of combustion increase; with the fine sizes an opposite tendency is shown, but with all grades the average magnitude of the relative rate characterizes the fuel grade. This comparison it will be observed, is simply a special adaptation of the air supply data.

75. *Comparison of Horse-power.* No fundamental unit of comparison of the power obtainable with various fuels is at hand as there is in the case of the rates of combustion. However, since at constant temperature of the gases the horse-power developed is principally determined by the rate of air supply, comparison upon the basis of equal rate of air supply and the actual horse-power obtained appears to be most logical. A comparison in this manner is made below. The results, however, apply only to the 210 H. P. boiler supplied by a grate area of 38.2 sq. ft., and since actual figures and not ratios are compared, accuracy in this demands that the air supply in each case should be the same. In the comparisons made, horse-power values at rates of air supply closely agreeing in value with the rate of air supply taken as a reference datum, have been chosen and a correction has been applied in each case by multiplying the values by the ratio of the unit rate of air supply chosen to the actual rate of air-supply, the assumption being that for moderate variations in the rate of air supply and horse power, the efficiency variation would be negligible.

1. Air supply, cu. ft. per second = 1.5×38.2

Test No.	Fuel	Air Supply	H. P.	H. P. Corrected to basis of 1.5 cu. ft. of air supply
30	5.1610 W	1.421	215.3	227.0
34	7.1610 —	1.507	231.9	231.0
43	5.1006 W	1.503	271.5	270.5
63	4.0703 W	1.480	283.1	286.7

2. Air supply, cu. ft. per second = 2.0×38.2

Test No.	Fuel	Air Supply	H. P.	H. P. Corrected to basis of 2 cu. ft. of air supply
36	7.1610 —	1.943	275.0	282.9
44	5.1006 W	1.997	321.8	322.0
56	4.0300 W	2.095	210.4	201.0
47	6.0200 —	2.026	151.4	149.5

X. DRAFT AND DRAFT PRESSURE REQUIREMENTS OF THE DIFFERENT GRADES

76. Inspection of the draft pressure data given in Tables 5 to 14 and in the curves numbered 3 in Fig. 1, 3, 5, 6 and 8, will show the characteristic differences in the draft pressure requirements for various rates of combustion of different grades. The rate of increase of the drop in draft pressure through the fuel bed and grate as the rate of air supply is increased, is shown for five grades by the slopes of the curves in Fig. 10. The curves are shown to be straight lines within work-

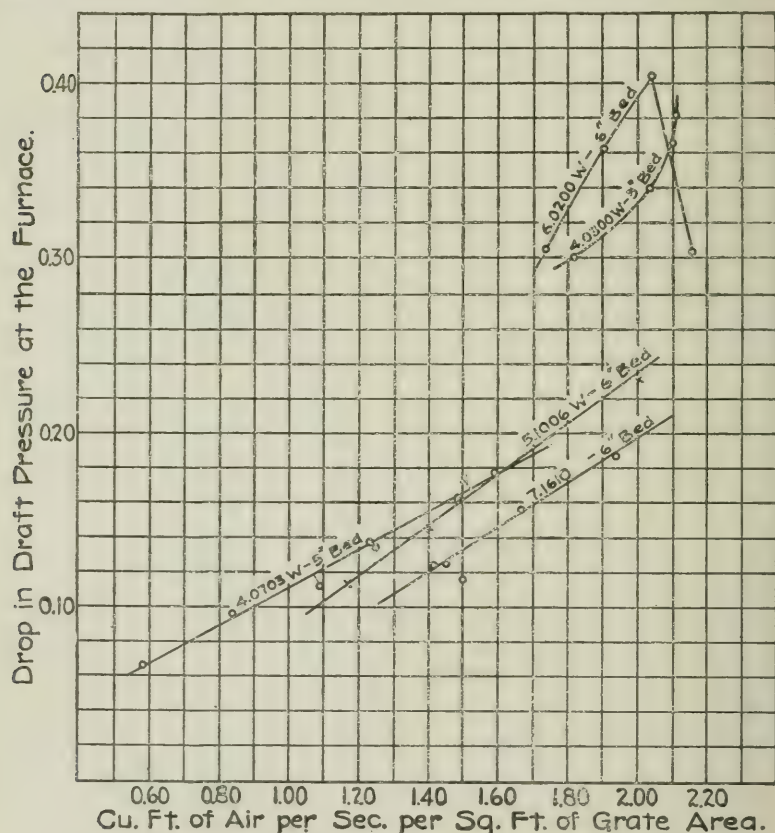


Fig. 10. Air Supply to Furnace and the Corresponding Drop in Draft Pressure.

ing range. Below the ranges shown, such curves, it is known, bend toward the horizontal. Variation from a straight line within the range of these experiments is due to an increased proportion of leakage induced by irregularities in the fuel bed or by clinker-ing or caking. The curve for fuel 4.0300 W shows the influence of gradually increased caking. As previously noted, the smaller grades, 6.0200 W and 4.0300 W reach a maximum respectively at about 2.0 and about 2.1 cu. ft. of air supplied per square foot of grate surface per second. The air actually passing through the fuel bed itself was, of course, in all cases less than the amounts shown.

77. *General Draft Relations.* For the purpose of showing the comparisons in Table 23, one test with a 5-in. fuel bed and at as

TABLE 23 AIR SUPPLY AND DRAFT PRESSURES FOR GRADES
TO DEVELOP THE BOILERS' RATED CAPACITY
5-inch thickness of fuel bed

Index No.	Test No.	Horse Power	Air Supply, cu. ft. per sq. ft. of Grate per sec.	CO ₂ Per cent	Drop in Draft Pressure through			Combustible Consumed per sq. ft. of Grate Surface per hour, pounds
					Fuel and Grate inches Water	Fuel, Grate and Boiler inches Water	Boiler inches Water	
1	2	3	4	5	6	7	8	9
5.1610 W	30	215.3	1.421	9.38	0.10	0.32	0.22	19.61
7.1610—	31	216.2	1.408	9.32	0.09	0.32	0.23	19.32
5.1006 W	38	211.5	1.102	11.09	0.09	0.23	0.14	17.85
4.0703 W	60	214.8	1.088	11.26	0.11	0.24	0.13	18.27
4.0700 W	17	213.3	.....	.....	0.13	0.45	0.32	19.92
5.0602 W	8	216.3	.....	.....	0.09	0.32	0.23	19.71
6.0402 W	23	207.6	.....	.....	0.11	0.35	0.25	17.28
4.0306 W	56	210.4	2.095	6.90	0.38	0.89	0.51	21.70
6.0200 W	52	175.5	1.933	6.20	0.36	0.83	0.47	17.80

nearly boiler rating as possible, was made with each grade.

Tests 8 and 17 as elsewhere explained are not directly comparable with the tests of the remaining grades. With increased attention to the fuel bed for those tests, less air for the same horse-power would have resulted, and consequently the draft pressure drop through the boiler would have been less. With fuel 6.0200 W, 173.5 horse-power was developed. The builders' rated horse-power as previously noted was not obtainable with that fuel. Air supply figures are not calculated for

those tests for which the flue gas samples were unsatisfactory.

In these tests, as in all tests, the quantity of excess air could have been reduced by keeping the fuel slightly banked at the rear of the grate. In so operating, increased temperature of the furnace gases and corresponding decreased draft requirements throughout for the same horse-power developed would result, but with uncertain effect upon the ashpit loss and the over-all economy.

XI. AIR SUPPLY

78. In Table 24 are presented the various air supply data for tests 28 to 64. A description of the manner of taking the gas samples, upon the analyses of which computations of these items are based, is given on page 117. The items of columns 3 and 4 have been referred to the basis of one pound of combustible consumed. Multiplying them by the factor $(100-c) \div 100$ will convert them to the basis of one pound of combustible as fed, where c is the per cent of carbon in the ash and refuse referred to the combustible as fed. The ratios, columns 5 and 6 and the rate column 8 are, of course, independent of the fuel unit.

The items in the various columns were calculated as follows:

Column 3. Weight of air supplied per pound of combustible consumed,

$$= \frac{N}{.33 (CO_2 + CO)} \times \frac{C - c}{100 - c},$$

where N , CO_2 and CO denote respectively the percentages of nitrogen, carbon dioxide and carbon monoxide in the flue gases as given in Table 36, C denotes the per cent of carbon in the combustible = Item 37.1, Table 39, and c the per cent of combustible in the carbon lost in the ash and refuse. Column 5, Table 15.

Column 4. Weight of air used per pound of combustible consumed,

$$= \frac{N - 3.77 \times O}{.33 (CO_2 + CO)} \times \frac{C - c}{100 - c},$$

where O denotes the percentage of oxygen in the flue gas.

This item gives the minimum air requirement for the combustible composition consumed.

Column 5. Ratio of air used to air supplied, per cent,
 $= \text{Column 4} \div \text{Column 5}.$

It also may be obtained directly from the flue gas analysis by means of the formula,

$$\frac{\text{Air used}}{\text{Air supplied}} = \frac{N - 3.77 \times O}{N}$$

Column 6. Ratio of excess air to air used, per cent,
 $= \frac{3.77 \times O}{N - 3.77 \times O}$

Column 7. Weight of dry flue gases per pound of combustible fed,
 $= \frac{11 \text{ CO}_2 + 8 \text{ O} + 7 (\text{CO} + \text{N})}{3 (\text{CO}_2 + \text{CO})} \times \frac{C - c}{100}$

Column 8. Cu. ft. of standard air per sq. ft. of grate surface per sec.,
 $= (\text{Column 3} \times \text{lb. of Comb. consumed per sq. ft. of grate surface per Hr.} \times 12.39) \div 3600.$

79. The resulting air supply items of this table are extremely interesting in that they show the principal cause of variation in the economic results of the tests. The relation thereto and the relation to the rate of combustion have been discussed in the preceding pages.

TABLE 24 AIR SUPPLIED

No.	Laboratory File No.	Air per lb. of Combustible Con- sumed		Ratio of Air Used to Air Supplied, per cent	Ratio of Excess Air to Air Used, per cent	Dry Flue Gases per lb. of Combustible Fed, pounds	Cu. ft. Standard Air per sec. per sq. ft. of Grate Surface
		Lb. Supplied	Lb. Used				
1	2	3	4	5	6	7	8
28	93-5.1610 W	22.28	11.67	52.4	90.94	22.19	1.484
29	94- "	22.21	11.60	52.3	91.51	21.94	1.457
30	95- "	21.05	11.58	55.0	81.76	20.75	1.421
31	96-7.1610-	21.55	12.05	55.8	79.29	21.00	1.432
32	97- "	21.88	11.82	54.0	85.09	21.63	1.423
33	98- "	20.85	11.72	56.2	77.93	20.65	1.466
34	99- "	20.83	11.73	56.3	77.56	20.60	1.507
35	100- "	21.30	11.96	56.9	75.70	20.50	1.692
36	101- "	21.67	11.75	54.2	84.41	21.43	1.943
37	102-5.1006 W	19.00	11.96	62.9	58.82	18.99	1.278
38	104- "	17.93	11.81	65.8	51.81	17.86	1.102
39	107- "	18.50	12.05	65.1	53.52	18.38	1.166
40	109- "	18.83	11.86	63.0	58.70	18.75	1.233
41	110- "	17.25	11.37	65.9	51.73	17.32	1.396
42	112- "	17.91	11.58	64.6	54.83	17.62	0.980
43	113- "	17.86	11.40	63.8	56.65	17.89	1.503
44	114- "	19.27	11.28	58.5	70.82	19.28	1.997
45	115-6.0200 W	41.77	11.73	28.2	256.11	38.54	1.919
46	116- "	39.84	11.65	29.2	241.86	38.35	2.154
47	117- "	35.41	11.72	33.2	202.25	35.08	2.026
48	118- "	32.64	11.51	35.2	183.64	31.72	1.888
49	119- "	38.00	11.72	30.9	224.33	36.34	1.735
50	120- "	32.23	11.60	36.0	177.93	30.80	1.759
51	121- "	33.20	11.65	35.1	185.12	32.17	1.860
52	122- "	31.56	11.71	37.2	169.47	30.76	1.933
53	124-4.0300 W	28.93	11.35	39.3	154.85	27.33	2.036
54	125- "	31.25	11.56	37.0	170.45	29.65	1.808
55	126- "	29.37	11.58	39.4	153.57	27.94	2.093
56	127- "	28.05	11.89	42.4	135.87	26.40	2.095
57	128-4.0703 W	17.54	11.43	65.2	53.46	17.32	1.250
58	129- "	17.79	11.43	64.4	55.70	17.82	1.266
59	130- "	15.66	11.21	71.6	39.67	15.52	0.847
60	131- "	17.30	11.21	64.8	54.34	17.31	1.088
61	132- "	17.78	11.36	63.9	56.52	17.72	1.230
62	133- "	17.90	11.30	63.1	58.47	17.87	1.589
63	134- "	17.52	11.33	64.7	54.63	17.47	1.480
64	135- "	15.45	11.20	72.5	37.88	15.49	0.655

APPENDIX I
THE TESTING PLANT

APPENDIX I

THE TESTING PLANT

81. *Equipment Used.*—The equipment especially provided for the steaming tests of fuels is located in the south bay of the Mechanical Engineering Laboratory. It includes a 210 horse-power Heine water-tube boiler, designed for a working pressure of 160 pounds, a Green traveling link grate and furnace, a Sturtevant induced draft apparatus and economizer,* and the usual small auxiliary apparatus. Additional equipment for use in experimental investigations includes the usual and special apparatus for weighing the coal and ash, for weighing and measuring feed water, for determining pressures, temperatures, and the quality of the steam, and for sampling and analyzing gases. Special apparatus for high temperature measurements which are available includes the Wanner optical pyrometer, Fery radiation pyrometer, thermo-electric, and platinum resistance thermometers.

82. *General Plan.*—The general plan of the testing plant is shown in Fig. 11. This arrangement was adopted with the object of facilitating experimentation, but was limited somewhat by the available floor area. The space occupied by the plant is 30 by 45 feet. The floor is of concrete, and all water supply pipes, drains, exhaust pipes from the auxiliary engines, and the blow-off pipes from the boiler, are laid in concrete trenches which connect at the rear of the plant with a 24-by 24-inch branch of the main laboratory pipe tunnel. The trenches are covered with cast-iron floor plates flush with the floor. The 24- by 24-inch trench, carrying the blow-off pipe and drains, leads through the south wall of the building and discharges into a creek running near by.

To provide easy access to the breeching and upper parts of the boiler, there is a deck surrounding the setting on three sides and extending to the south wall of the building at an elevation of $10\frac{1}{2}$ ft. This is constructed of iron channels supported by iron columns and wall brackets. The floors are of iron grating and plates. It extends along the west wall and joins the central gallery of the building, and along the south wall toward the rear of the boiler room opens into a 14 by 24 ft. laboratory at the same elevation, (Fig. 11 and Fig. 14.) At the front of the boiler, (Fig. 12,)

*Not used in the present experiments.

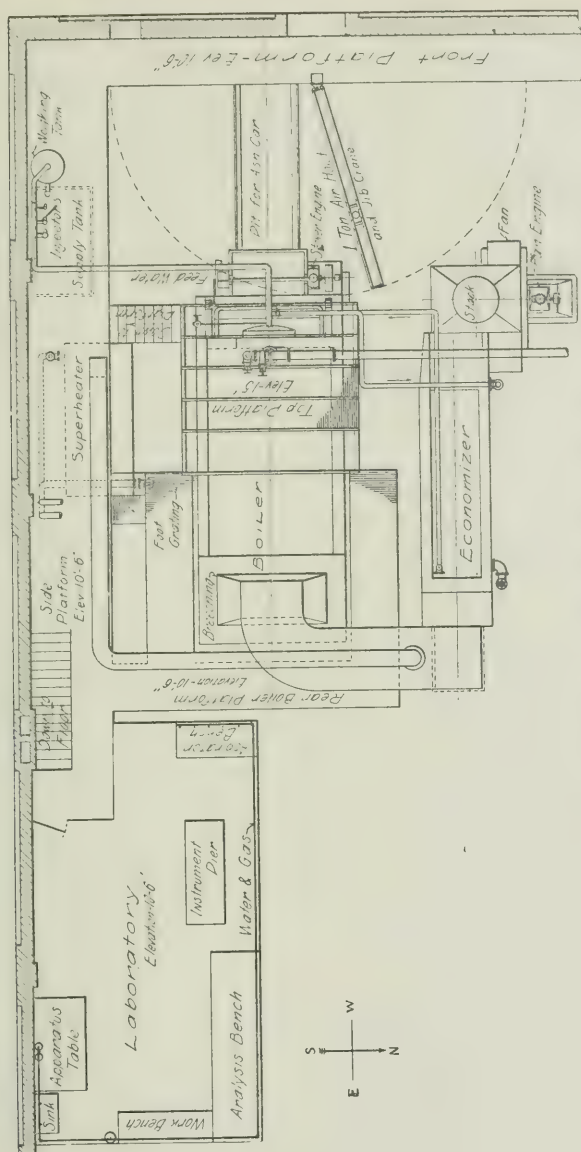


FIG. 11 GENERAL PLAN OF THE TESTING PLANT.

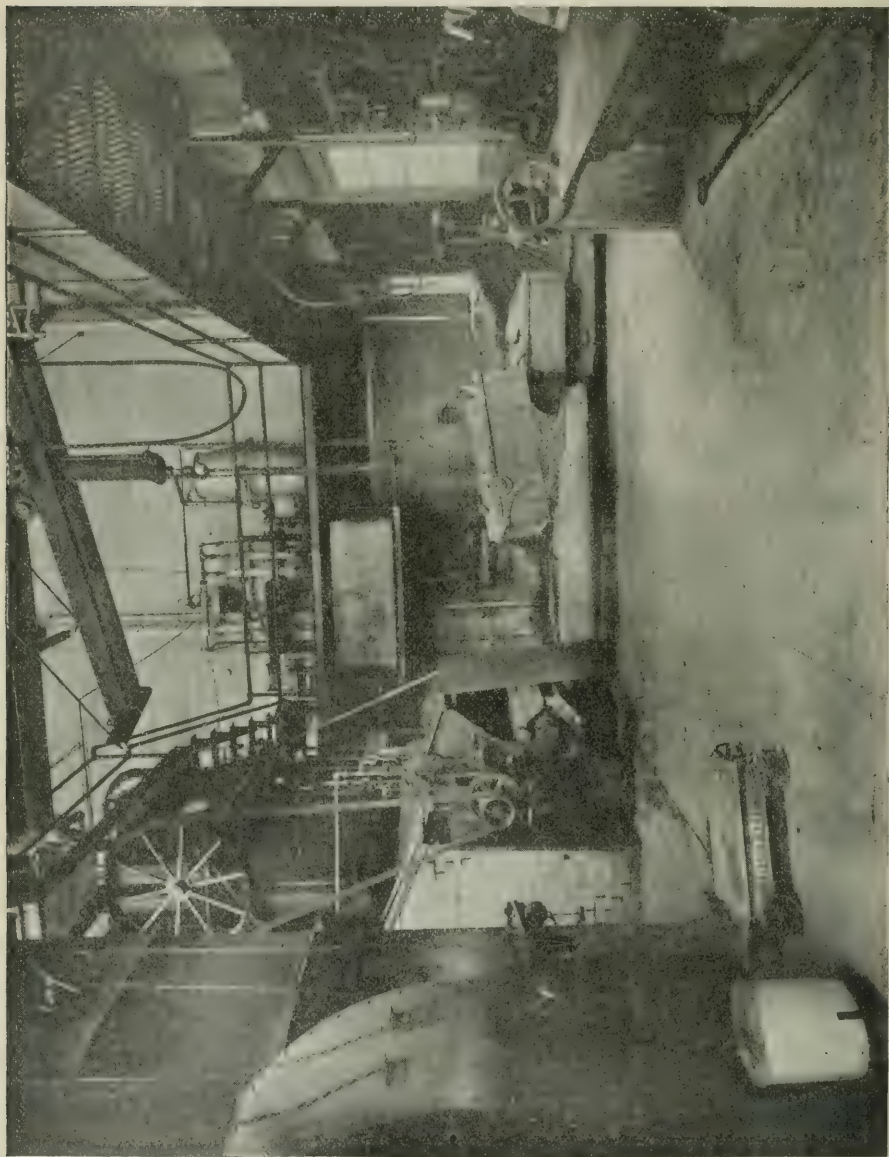


FIG 12. FRONT VIEW OF BOILER ROOM

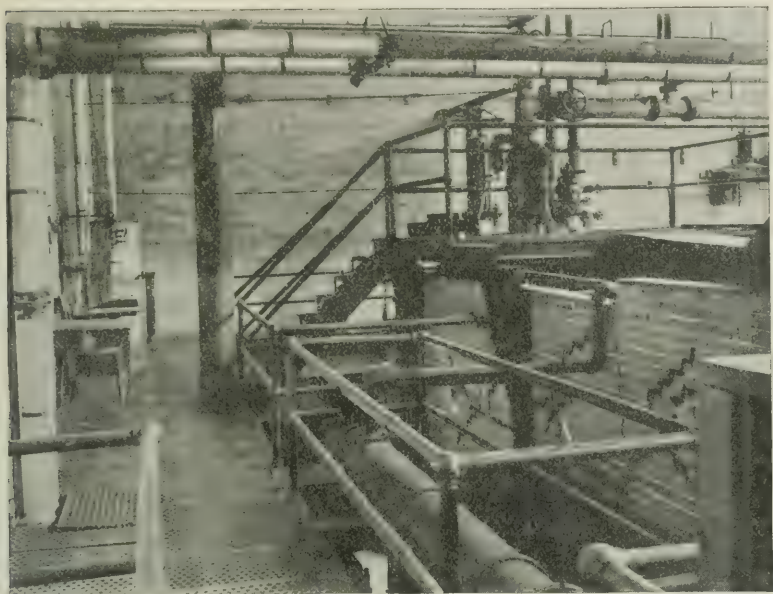


FIG. 13. ARRANGEMENT OF THE UPPER DECKS



FIG. 14. LABORATORY FOR GAS ANALYSIS

a short stair leads to a platform grating surrounding the uptake and header, and on the main deck at the foot of these stairs are located the feed water weighing tank and injectors. The 14-by 24-ft. laboratory, Fig. 14, is used for all observations that can be made at a distance from the boiler. Here are located the aspirators for drawing gas samples, apparatus for gas analysis and the various kinds of indicating and recording apparatus for temperature measurements. A 3-by 7-ft. stone-capped instrument pier is provided to support galvanometers and delicate instruments.

Fig. 11 shows, also, the location of a Foster independently fired superheater which is a part of the general equipment of the Steam Engineering Laboratory.

82. *Boiler and Combustion Chamber.*—The Heine water-tube boiler installed in this plant is similar in every respect to the boilers which were in use for some two years at the fuel testing plant of the United States Geological Survey at the World's Fair Grounds, St. Louis, and with the exception of material used in the construction, the setting is the same and the boilers similarly baffled. The essential difference is in the furnaces, the Geological Survey's boilers being equipped with plain and with rocking grates.

A sectional elevation of the boiler is shown in Fig. 15 and the baffling and other features of the setting in Fig. 16. The walls of

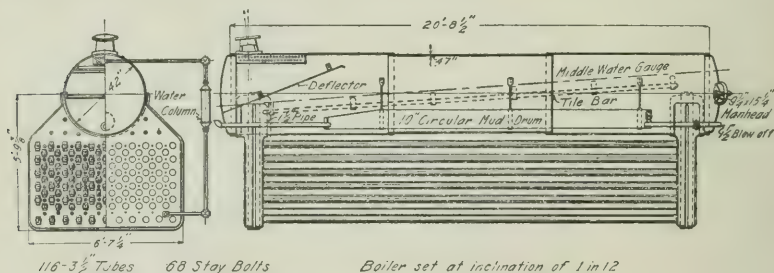


FIG. 15. DETAILS OF THE 210 H. P. HEINE BOILER

the setting are 20 in. thick with a 2-in. air space as shown. Hard face brick, closely laid, were used on the outside walls, and in the furnace, combustion chamber and gas passage, the fire brick lining extends to the top row of tubes. Regular Heine *C* tube tiles are used in the construction of the combustion chamber roof which extends to within 43 inches of the rear water leg.

83. *The Principal Dimensions of the Heine Boiler, and the traveling link grate and furnace are as follows:*

Rated horse-power.....	210.0
Number of steam drums	1
Length of steam drum.....feet.....	21.583
Inside diameter of drum.....inches.....	42
Number of tubes.....	116
Outside diameter of tubes	inches..... 3.5
Inside diameter of tubes.....	inches..... 3.26
Mean length of tubes exposed to gases....	feet.... 17.875
Kind of grate.....	Green traveling link
Width of grate.....	inches..... 54
Effective length of grate.....	inches..... 102
Area of grate surface.....	sq. ft..... 38.2
Area of air space in grate.....	sq. ft..... 8.25
Ratio of air space to grate area.....	0.216
Mean height of furnace between ignition arch and bridge wall.....	inches..... 48
Length of ignition arch.....	inches..... 48
Mean height of ignition arch.....	inches..... 15
Kind of draft.....	Induced
Height of stack above grate.....	feet..... 45.5
Diameter of stack.....	inches..... 40.0
Sectional area of stack....	sq. in.....1250
Area of gas passage over the bridge wall..	sq. in.....1665
Smallest area of gas passage between grate and lower baffle.....	sq. in.....1665
Area of opening through lower baffle.....	sq. in. ....1677
Smallest area of gas passage between upper and lower baffle.....	sq. in.....1612
Area of opening through upper baffle.....	sq. in..... 746
Area of gas passage entering breeching ...	sq. in..... 625
Ratio of smallest gas passage to grate area.....	.113
Water heating surface in tubes.....	sq. ft.....1900
Water-heating surface in shell, legs, etc....	sq. ft..... 127.4
Total water-heating surface.....	sq. ft.....2027.4
Ratio of heating surface to grate surface.....	53.1
Total water space....	cu. ft..... 273
Total steam space.....	cu. ft..... 85

84. *Grate and Furnace.*—The traveling link grate, Fig. 17, and furnace are the standard type supplied by the Green Engineering Company. Two features of this grate are the long flat ignition arch and the high bridge wall. The special ledge plates shown in the section *B B*, Fig. 16, are, however, a slight modification of the standard installation, being so designed that for experimentation, a change can be made to a hand-fired grate without changing the walls of the setting.

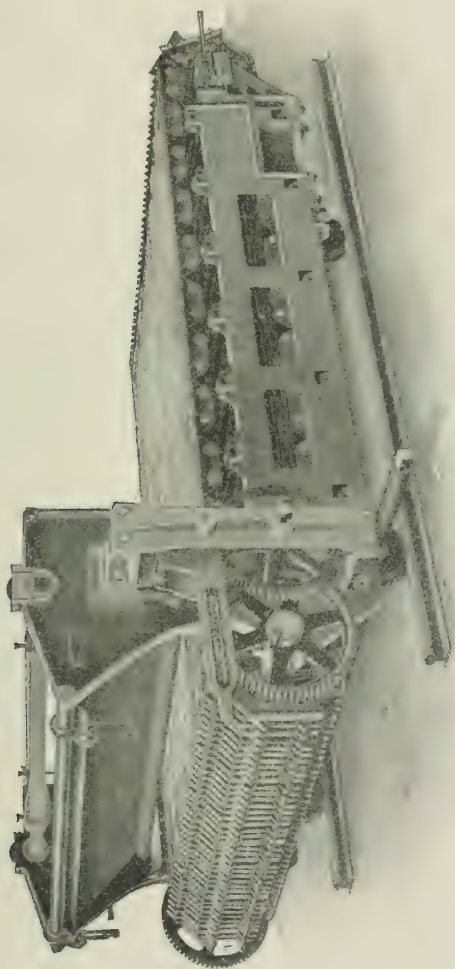


FIG. 17. THE GREEN TRAVELING LINK GRATE

85. *The Water-Back.*—The Harrington automatic water-back installed with this grate is indicated at *H* in Fig. 16. It consists of two connected iron cylinders extending across the width of the grate, supported by the furnace settings and so hung that the lower one rides upon the ash and clinker, and is free to move in a circular arc about the axis of the upper stationary cylinder. The free adjustability of the lower cylinder necessitates a flexible coupling to the water supply and for this reason the circulating water is supplied independently of the boiler.

86. *Ash Handling.*—Ash from the grate is removed by means of a car which runs along a track at the bottom of the ash tunnel to the front of the boiler, where it is handled by a one-ton air hoist and jib crane for removal to trucks, or, first, to scales for weighing as desired. The ashpit is provided with a concrete hopper fitted with a hinged door so that the ash may be retained in the hopper while the ash car is being emptied.

87. *Induced Draft.*—The plan and elevation of the induced draft system and economizer are shown in Fig. 18. By reference

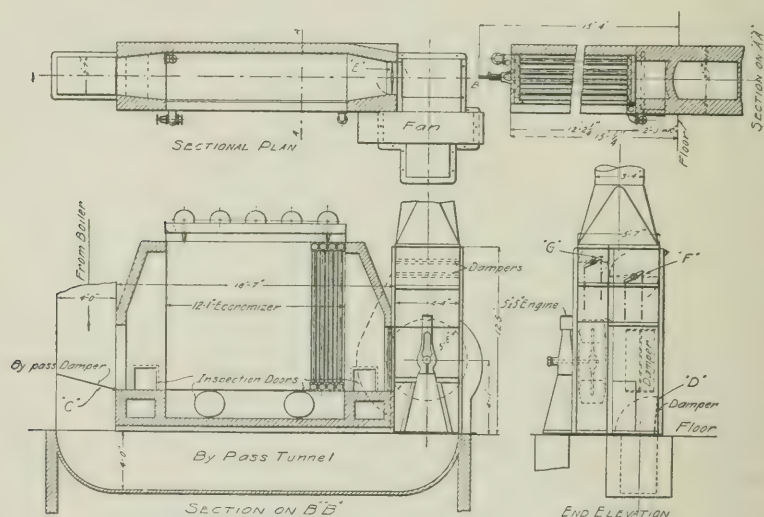


FIG. 18. SECTIONAL VIEWS OF THE INDUCED DRAFT SYSTEM AND THE ECONOMIZER.

to this it will be seen that there is a by-pass tunnel for the escaping gases so that when it is desired to cut out the economizer, damper *C* can be thrown to a vertical position, damper *E* set

at right angles to the center line of the economizer, and *D* raised to a vertical position. Provision is also made for direct chimney draft by leaving damper *G* as shown and setting *F* vertical, the draft pressure being controlled by an independent damper in the breeching or by the damper *F*. The height of the stack, however, is not sufficient for operation under chimney draft.

The fan is a regular Sturtevant steel plate exhaust fan with blast wheel $5\frac{1}{2}$ ft. in diameter and $22\frac{1}{2}$ in. in width, directly connected to a 5 by 5 upright enclosed engine mounted on a sub-base which stands directly against the fan housing. The inner bearings of the engine are water cooled. Since installation, this engine has been fitted with a Waters' throttling governor.

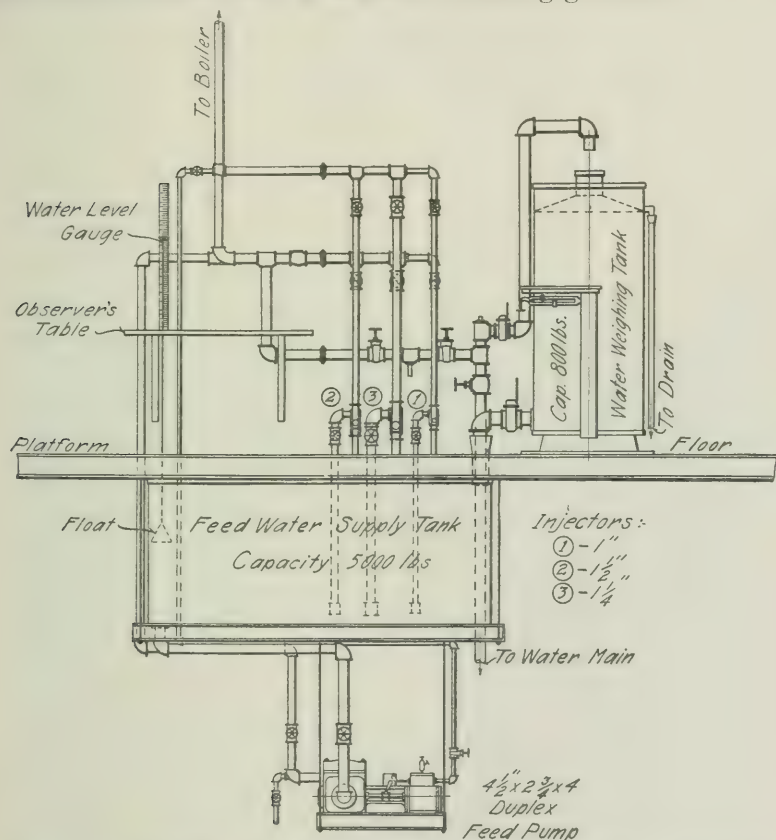


FIG. 19. SHOWING ARRANGEMENT OF WATER-WEIGHING APPARATUS, INJECTORS, PUMP, ETC.

88. *The Economizer.*—The economizer was not used in these tests, but to complete the description of the plant a description is given. This economizer, one of B. F. Sturtevant Company's standard design, consists of 80 pipes, 4 9-16 in. outside diameter and 9 ft. in length, giving a total heating surface of 1001 sq. ft., (4.77 sq. ft. per rated boiler horse-power independent of economizer), and a capacity of 5040 lb. of water. The pipes are arranged in twenty sections of four pipes each, and are staggered. The location of the economizer is shown in Fig. 11. The feed water connections are by-passed so that the economizer may be cut in or out at will. During the series of tests reported in this paper, the connections between the boiler and economizer were removed.

89. *Piping.*—For supplying feed water to the boiler there are provided both injectors and a $4\frac{1}{2}$ - by $2\frac{3}{4}$ - by 4-inch duplex steam pump; the latter is controlled by a Vigilant feed water regulator. All steam and feed lines are well lagged with magnesia covering, and all water by-pass valves are in duplicate, and the intervening dead space vented so that no undetected leakage can occur; flanged couplings are also used to provide for blanking off the by-pass lines when necessary. A similar arrangement of stop-off valves and vents is used for detecting leakage through the blow-off valves.

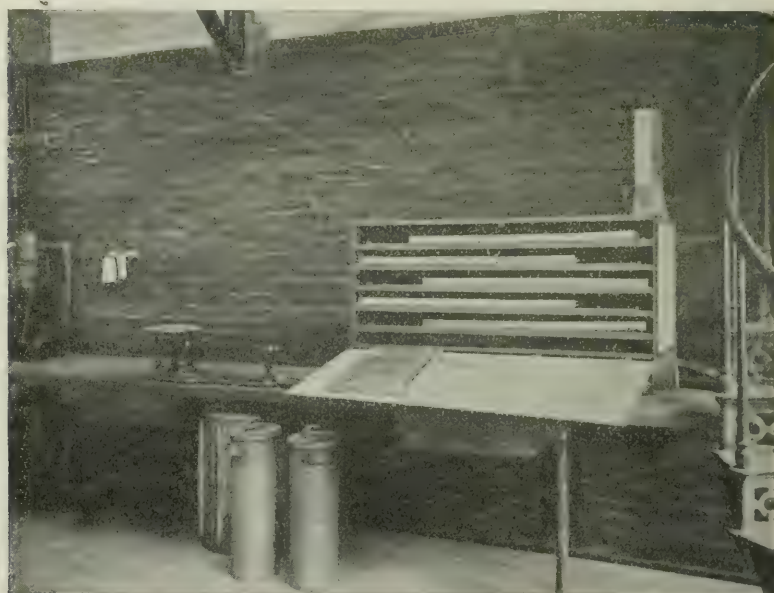


FIG. 20. OVEN FOR AIR-DRYING COAL SAMPLES

90. *Setting Wall Diagrams.*—The diagrammatic sketches, Fig. 21 and 22, which show opposite sides of the boiler setting, give the location of the points at which various routine and special observations have been taken. They are the permanent lab-

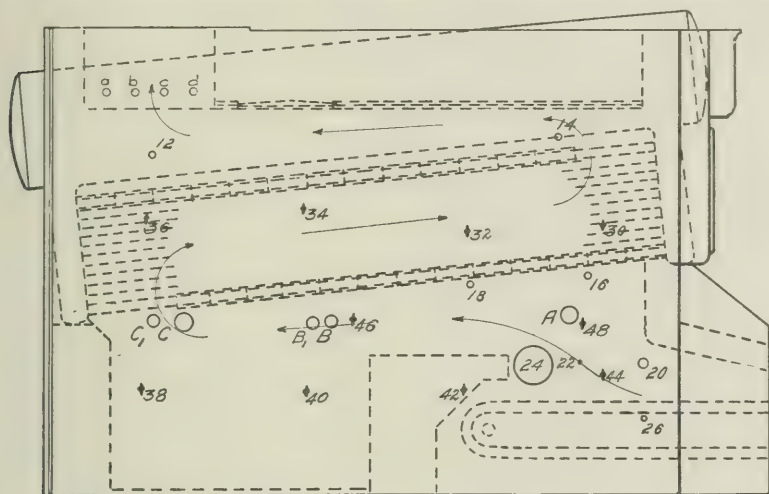


FIG. 21. NORTH SETTING WALL

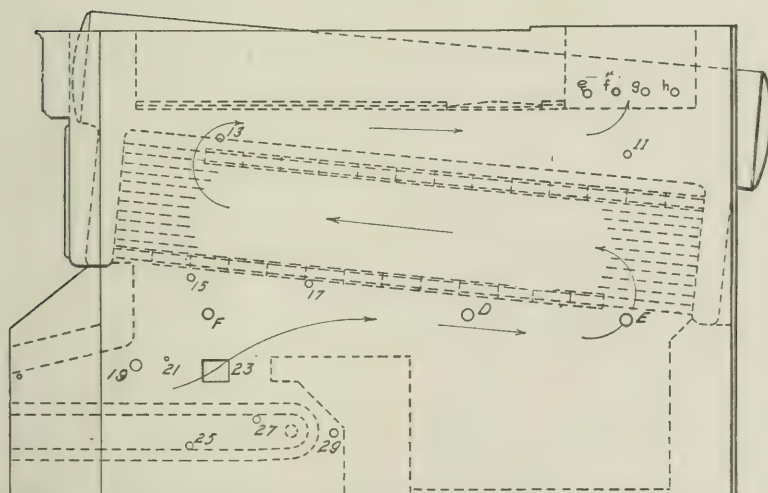


FIG. 22. SOUTH SETTING WALL

oratory record of such locations, consequently some openings appear in the diagram which have been subsequently closed.

The points 11 to 29, excluding 23 and 24, which are the furnace inspection doors, are openings used at various times for the measurement of draft pressure and temperature observations within the furnace or gas passage.

Openings *a*, *b*, *c*, *h*, were used for special investigations relating to methods of gas sampling. See page 88. The points numbered in even numbers from 30 to 48 show the location of mercury thermometers imbedded in the surface of the wall; they are useful in keeping a check on the wall temperature.

The openings *A*, *B*, *B*₁, *C*, (Fig. 21), etc., are used for special furnace temperature measurements with various types of pyrometers and for observations relating to the extent of the flame within the combustion chamber. They consist of iron pipes extending through the walls and capped on the outer end. The interior is observed through smaller holes in the caps, and the holes closed by sliding shutters between observations.

APPENDIX II

EXPERIMENTS RELATING TO FLUE GAS DATA AND METHODS
OF MAKING AND RECORDING FURNACE OBSERVATIONS

APPENDIX II

SAMPLING FLUE GASES

91. It is common experience that samples of flue gas taken simultaneously at different points across any section of the gas stream flowing through a boiler, show different proportions of air and combustion gases. This condition is due to the fact that the air supplied to the furnace is never uniformly distributed, and does not become diffused in the passage through the boiler; also, unless the utmost care is observed, samples taken at the breeching or across the base of the stack may be further affected by leakage of air through the setting. The worst feature of the latter occurrence, even when the analysis is desired only for computation of heat loss, is that such excess air has even less chance to become diffused than that entering the furnace.

92. For the purpose of determining what the actual conditions were in this experimental plant, eight separate sampling pipes, perforated with $\frac{1}{8}$ in. holes along their full length were inserted at points *a*, *b*, *h*. See Fig. 21 and 22, page 85. The setting walls are of pressed brick and every precaution was taken to insure against leakage of air into the gas passages between the furnace and sampling tubes. The sampling tubes were connected by separate tubes to a large Richards aspirator. While the gas was thus being drawn at a uniform rate for all tubes, one-minute samples were simultaneously drawn from the tubes through connections. Four sets of samples were drawn in this manner on different days. Analyses of these are given in Table 25, which shows the percentage by volume of carbon dioxide in the gases.

TABLE 25 VARIATION IN FLUE GAS SAMPLES

Carbon Dioxide per cent	Trial	TUBES							
		a	b	c	d	e	f	g	h
	A	4.2	4.8	4.6	4.6	5.6	4.2	5.2	4.2
	B	4.8	5.4	5.1	...	7.1	7.1	7.1	4.5
	C	7.2	8.4	10.6	10.8	8.8	6.2	7.2	5.8
	D	7.5	8.0	9.6	10.4	10.2	9.6	8.8	7.3

93. The imperfect mixing of the gases and air as they come from the furnace is attributed to the fact that free air enters along

the sides and rear of the grate, and as there are no mixing baffles in the furnace and the boiler is baffled horizontally, the different streams are never wholly intermixed. The outside streams are consequently diluted. Tracing the course through the boiler of an imaginary layer of free air flowing into the furnace at the rear of the grate, will afford sufficient explanation for the difference in dilution shown.

94. As a result of the conditions disclosed by these results, it was decided to try some means of mixing the gases, the outcome of which is the device shown in Fig. 23. This arrangement con-

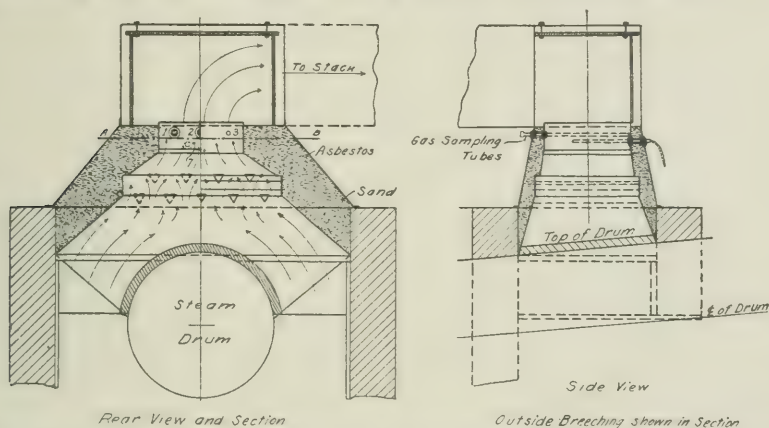


FIG. 23. SECTIONS OF BREECHING SHOWING FLUE GAS MIXING BAFFLES AND SAMPLING TUBES

sists of a well insulated false or inner breeching, within which the gases are compelled to pass through a series of mixing baffles and converge into an uptake constricted to 21 by 21 in., the latter forming a sampling section across which the gases are thus compelled to flow with nearly uniform velocity. To prevent leakage from the outer breeching into this inner breeching, all seams are effectually closed with iron cement, the filling of insulating sand acting as a further precaution.

95. Three gas sampling tubes 1, 2, and 3, Fig. 23, consisting of $\frac{3}{8}$ -in. pipe, capped on the inner end, and perforated with a double row of $\frac{1}{16}$ -in. holes spaced 3 in. apart along the under side, were equally spaced across the gas passage. These were brought together on the outside by means of $\frac{1}{4}$ -in. lead pipe uniting in a junction box, from which a single lead pipe conducted the gas sample to the gas apparatus and aspirator. By means of tees in

the leads to the junction box, simultaneous samples could be drawn from each of the separate tubes while the aspirator was in action drawing the regular test sample. A number of samples were taken in this manner during several tests, care being taken as in the previous experiments that the rate of sampling from each tube was equal. The results of analyses of these samples are given in Table 26 and 27. An inspection of the results shows that marked improvement in the sample was thus effected.

TABLE 26 COMPARISON OF GAS SAMPLES DRAWN FROM SEPARATE TUBES FIG. 23

No.	Per cent Carbon Dioxide				No.	Per cent Carbon Dioxide			
	Tube No. 1	Tube No. 2	Tube No. 3	Average		Tube No. 1	Tube No. 2	Tube No. 3	Average
1	7.6	7.2	6.9	7.2	18	11.7	11.7	11.4	11.6
2	7.5	7.0	6.8	7.1	19	10.7	10.0	8.5	9.7
3	7.5	7.1	6.8	7.1	20	9.8	8.9	8.0	8.9
4	11.1	10.9	10.6	10.9	21	9.9	9.9	8.8	9.5
5	9.8	9.5	9.4	9.6	22	11.2	10.0	9.0	10.1
6	4.5	4.7	4.9	4.7	23	10.1	9.7	9.0	9.6
7	3.9	3.7	3.7	3.8	24	11.4	11.5	11.2	11.4
8	6.8	6.1	6.0	6.3	25	11.0	11.1	11.0	11.0
9	6.7	6.5	5.8	6.3	26	9.2	9.2	9.2	9.2
10	6.7	6.1	5.9	6.2	27	8.5	8.6	8.3	8.5
11	6.2	6.0	5.8	6.0	28	11.1	10.5	10.5	10.7
12	8.2	7.1	6.6	7.3	29	12.6	11.1	10.7	11.5
13	12.8	11.1	10.8	11.6	30	13.6	13.9	13.8	13.8
14	12.5	11.2	10.8	11.5	31	9.9	10.0	9.8	9.9
15	11.9	11.3	10.5	11.2	32	12.3	10.8	10.5	11.2
16	13.9	13.8	13.4	13.7	33	10.2	9.2	9.0	9.5
17	12.1	11.6	10.9	11.5	34	9.6	9.6	9.3	9.5

TABLE 27 COMPARISON OF GAS SAMPLES DRAWN FROM SEPARATE TUBES FIG. 23

No.	Carbon Dioxide				Oxygen				Nitrogen			
	Tube No. 1	Tube No. 2	Tube No. 3	Av.	Tube No. 1	Tube No. 2	Tube No. 3	Av.	Tube No. 1	Tube No. 2	Tube No. 3	Av.
1	5.7	5.8	5.7	5.7	14.4	14.3	14.3	14.3	79.9	79.9	80.0	79.9
2	8.1	7.8	7.5	7.8	11.6	11.9	12.2	11.9	80.3	80.3	80.3	80.3
3	8.5	7.7	7.5	7.9	11.5	12.4	12.7	12.2	80.0	79.9	79.8	79.9
4	7.6	7.2	6.9	7.2	12.1	12.5	12.8	12.5	80.3	80.3	80.3	80.3
5	7.5	7.0	6.8	7.1	12.1	12.7	12.8	12.5	80.4	80.3	80.4	80.4
6	7.5	7.1	6.8	7.1	11.7	12.8	13.1	12.5	80.1	80.8	80.1	80.3
7	13.9	13.8	13.4	13.7	5.8	5.8	5.8	5.8	80.3	80.4	80.8	80.5
8	12.1	11.6	10.9	11.5	6.7	7.4	8.3	7.5	80.8	81.0	81.2	81.0
9	9.4	8.8	8.3	8.8	10.2	10.9	11.3	10.8	80.4	80.3	80.4	80.4

96. *Improved Form of Gas Sampling Tubes.* At the close of the present series of tests, an improved form of gas sampling tube designed by the writer was introduced. This consists of a pair of tubes intended to compensate for drop in pressure along the tube. See Fig. 24. The lower parts of the loops are per-

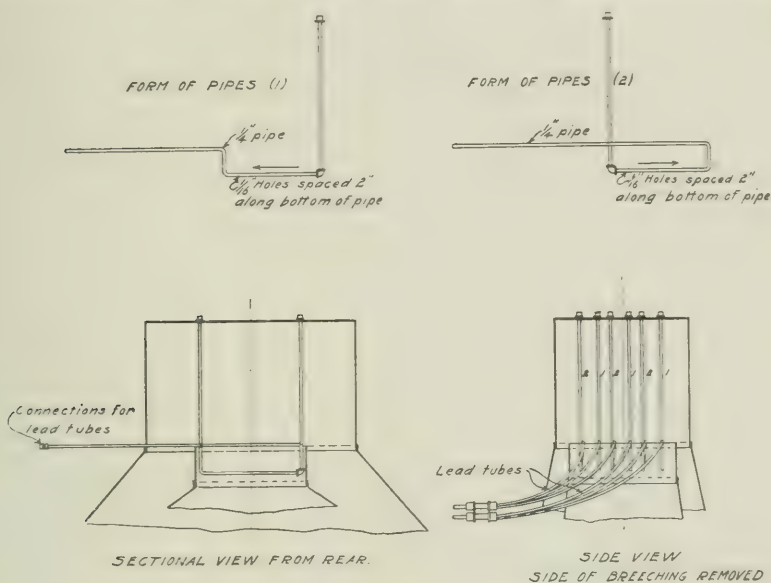


FIG. 24. IMPROVED FORM OF GAS SAMPLING TUBES

forated with single rows of $\frac{1}{16}$ -in. holes spaced two inches apart, the gas traveling in the direction of the arrows. The other sampling pipes were removed and three pairs of these tubes placed across the sampling box. The tubes drop into the sampling box from above so that perforation of the box is avoided and the possibility of leakage is further eliminated. At the outside, the pipes are brought together by means of $\frac{1}{4}$ -in. lead tubing, into a junction box from which a $\frac{1}{4}$ -in. lead tube conducts the gas to the apparatus bench and thence to the aspirator as before. The capped ends of the sampling tubes are bent upward and pass out through the breeching to facilitate cleaning. Just previous to the start of each test the tubes are cleaned with compressed

air, which is applied through the junction box, and the end caps are removed occasionally to permit blowing out dust which gradually accumulates at the bend near the last hole. Special tests of the new sampler have not been made so that it is not known whether any real advantage has resulted.

97. It should be remembered that this gas mixing device was designed to meet special conditions brought about by the course which the gases take in leaving this boiler and by the sharp angle in the breeching just above the boiler. It is possible that had the boiler been surmounted by a straight stack, other and more simple means could have been employed. The effect of the baffles on the draft is so considerable that it can be used only where high force of draft is available.

METHOD OF MAKING AND RECORDING FURNACE OBSERVATIONS

98. A careful record of the characteristics shown by the fuel bed is a necessity in the study and comparison of fuels. With the exception of the flue gas data, no other set of data is as generally useful in the analysis of variations which show up in the results. However, if such a record is to be of use, the relative value of various occurrences which affect the furnace and fuel performance must be clearly recognized and the notations which are made during the experiment, recorded in a systematic manner. Experience with the common methods of recording furnace observations and certain isolated test data in the form of running notes has shown the insufficiency of such methods for the purpose of a comparable record, not because such notes may not be made sufficiently full, but chiefly because of their lack of system both in arrangement and in the descriptive terminology used. To eliminate discordance from those sources in this series of tests and to provide for a general summary of the data, two convenient report forms were used.

99. See Form 1, p. 93; Form 2, 96-97. The description which follows will show the various purposes which these forms have served. Their presentation here is essential in that they will convey some idea of the effort made to secure consistent operation and comparable data.

100. *The Furnace Condition log* is a record of the various items included and affords a permanent record of variations in the operation of the grate and furnace.

101. *The Furnace Observer's Report*, which was always made out immediately upon the close of each test, takes care of the averages from the furnace log and a number of miscellaneous items, a permanent record of which is desirable. Further and of more importance, the report is intended to maintain a daily balance of the deductions reached, relative to the fuel, from the point of view of the furnace observer. An explanation of the various items is as follows:

THE FURNACE CONDITIONS LOG

"Condition of Fuel Bed at Rear of Grate"

In recording the degree of adherence to the conditions adopted for the control of the furnace and the fuel bed area, the following terms have been useful.

1. *"Banked"*—Live fuel against the water-back and thicker than at the center of the grate, live fuel also falling into the ash-pit.

2. *"Close"*—Live fuel against the water-back, but none passing to the ashpit.

3. *"Clear"*—Edge of fuel line completely burned out just at the water-back.

4. *"Inches of grate clear"*—Distance in inches, estimated, of the live fuel line from the water-back.

In using these terms the fuel was considered to be completely burned when both flame and incandescence had disappeared.

102. *Recording the Observations*—Observations relating to the area of the fuel bed were not made simply at the regular 15 minute periods. The three columns 2, 3 and 4, provide for a record of the maximum, minimum and average distances from the water-back, so that the record is really a continuous one. The average recorded is a weighted average, depending upon the judgment of the observer. It is not the mean of the maximum and minimum observations. A mica window in the inspection door allowed easy observation of the conditions within the furnace. The simple fact that continuous record is being kept of the maximum and minimum

area of the fuel bed has a salutary effect in preventing uncalled-for irregularities in the operation of the grate.

Change of Grate Speed—Column 5. In this column the number of adjustments found necessary to comply with the other requirements is recorded.

Average Area of Holes in the Fuel Bed—Column 6. Any entirely burned out spot in the fuel bed greater than six inches in diameter was considered a hole in the bed, and the average total area of these was recorded for each 15-minute period. The mean of column 6 was recorded on the Furnace Observer's Report, also the maximum and minimum area shown by the 15 minute readings.

A tabulation of the results of these observations, taken from the Furnace Observer's Report, will be found in Table 40.

Leveling the Fire—Columns 8 and 9 provide for recording the time of leveling. Leveling in the sense in which we have used the term does not have the significance for which it is used in a hand-fired furnace. That is, it does not signify that the whole fuel bed has been leveled. In these tests, whenever holes were leveled or fuel pushed to the sides of the grate, a, "leveling" was recorded. In the Furnace Observer's Report, in order to facilitate comparison, this item is based on a four-hour period.

Slicing—Column 10. Slicing the fuel bed in chain grate operation usually consists simply of running the slice bar along the ledge to remove any adhering clinker which might otherwise accumulate, to reduce the grate area or disturb the fuel bed along the sides.

A record of the number of slicings and the time at which they were made gives double assurance that trouble from this source has been avoided.

FURNACE OBSERVER'S REPORT

Items 1 to 8. These items are intended as a check on some of the principal items of the test. It was one of the duties of the furnace observer to assure himself of the accuracy of the recorded weight of fuel and to see that the general and special control conditions were carried out. Item 8 is intended to keep track of any change in the control conditions outlined for the test. This item often constitutes valuable data, especially when it is found that the fuel will not respond to the draft pressure assigned, and further keeps track of changes made upon verbal instruction which might be misunderstood.

File No. _____

Class _____ No. _____

Observer _____

Fuel Index No. _____

Firemen _____

Series Test No. _____

Date _____

FURNACE OBSERVER'S REPORT

1. Flues when last blown: time _____ A. M., _____ P. M., Date _____
2. Boiler and mud-drum when last blown off; Time _____ A. M., _____ P. M.
3. Time of starting test _____, time of closing test _____
4. Total pounds test fuel fired since last test _____
5. Total pounds test fuel fired during test _____
6. Thickness of fuel bed, inches _____
7. Av. difference of pressure above and below grate, in. of water _____
8. Change in control conditions preceding or during test _____

Why _____

SUMMARY OF FURNACE OBSERVATIONS

1. Conditions during the hour preceding start of test: Load _____
Draft, in furnace _____, in breeching _____
2. Conditions of fuel bed at rear of grate, per cent of time: Banked _____,
close _____, _____, nohes clear _____
3. Fuel bed sliced _____ time, leveled _____, times av. four hr. period.
4. Area of holes in fuel bed, sq. in. (average of column 6); _____
Max., for 15 min. period _____, Min. for 15 min. period _____
5. Grate speed, constant or variable? Av. speed sq. ft. per hour _____
6. Was load easily maintained? _____ Why? _____
7. Was maximum rate of combustion attained? _____
8. Estimated increase of capacity obtainable by forcing _____
9. Would lower draft increase the evaporation? _____
10. Considering previous tests on this fuel (Index No. _____) which condition if any necessitated:

(a) Least attention to fuel bed and grate_____

(b) Most attention to fuel bed and grate_____

11. The preceding tests in order of the most favorable conditions are,

_____Remarks_____

General Remarks

Note—A list of descriptive terms has been selected for use in describing the general characteristics of the fuel bed, flame, etc. These should be adhered to as closely as possible. See, "Instructions to Furnace Observer."

1. General appearance of fuel bed_____
_____2. Character of the flame_____
_____3. Appearance of refuse, clinker, etc._____
_____4. Change of firemen during test—time, etc._____
_____5. Change of furnace observer on this fuel_____

_____Remarks_____

Date_____

Signed_____

Summary of Furnace Observations

Item 1—This item relates to the condition of the fuel bed and furnace at the start of the tests.

Items 2, 3, 4 and 5—See under "Furnace Conditions" log above.

Items 6, 7, 8 and 9—Deductions entered under these items call into play the judgment of the observer. They are useful mainly in outlining further work on the fuel, though an observer of some experience will usually make very close deductions.

Items 10 and 11—Sub-items (a) and (b) are filled out after each test. They are useful in formulating the deductions called for under Item 11. The entry under the latter item and under "Remarks" summarizes the conclusions of the observer as far as his personal observations go.

General Remarks

Item 1—The entries under this item are difficult to systematize. The fuel bed may be open and burning evenly, broken and burning in spots, light and bulky, or it may lie on the grate in a compact mass with level surface. There are as many different modifications of fuel beds as there are kinds and grades of fuel. The fuel bed should be fully described, as upon its characteristics depend the distribution of the air supply and consequently the rate of combustion and the temperature obtainable.

Item 2—The amount of flame present in the furnace depends upon the amount of the volatile matter in the fuel and the proportion of air supplied. Observation of the flame is of interest chiefly in relation to the production or non-production of smoke. In the experiments flame which did not persist beyond point B (see Fig. 21, page 85) was denoted as "short" flame; flame which persisted beyond B was designated as "medium long" while flame of any volume entering the tube space at C, Fig. 16, was designated "long" flame. Flame, it should be understood, is long only because there is not sufficient oxygen in thorough mixture with the volatile matter to cause rapid combustion.

Item 3—Clinkering seldom gives serious trouble in chain grate operation. This item, however, takes care of any unusual occurrences.

Items 4 and 5—These items are intended to put on record in a conspicuous place any changes in the personal factor entering into the operation of the furnace.

APPENDIX III
EXPERIMENTAL METHODS

APPENDIX III

I. EXPERIMENTAL METHODS

An effort was made so to arrange the testing plant and to provide such instruments and facilities that the requirements of a test could be carried out with essential accuracy. In this appendix will be found a detailed description of the routine method pursued in collecting the data. The details of boiler performance are liable to so many uncertainties not accounted for in the mere statement of the code of the American Society of Mechanical Engineers that it is believed a description of the methods may assist engineers and students who may wish to make use of the collected data to give proper weight thereto.

In the tabulation of results, Tables 28 to 40, p. 121, the mean of the test readings from the observed data is given as recorded on the logs for each test, essential corrections to agree with the calibration of instruments having been made. Where data known to have been affected by inaccuracies are retained in the tables, attention is directed thereto in the itemized descriptions.

Weighing the Fuel and Ash.—In firing the furnace during a test, it has been found most satisfactory to feed the coal into the hopper by hand, although a specially designed coal bucket was available. The coal was weighed in a steel charging car made with one side hinged, shown in the photograph, page 76. The dimensions of this car are $2\frac{1}{2}$ ft. by $4\frac{1}{2}$ ft. by $1\frac{1}{2}$ ft. deep, and its capacity was about 700 lb.

During the tests, 500 lb. of coal was weighed at a time, the coal feed hopper was kept continually heaped a little more than full, and after each 500 lb. charge had been shovelled into the hopper, the coal was allowed to feed until a straight edge drawn across the top would give a level just even with the top edges of the hopper. The interval of time elapsing was recorded as the time of firing the charge. Other readings coincident with the time of firing were height of water in the water gage and the level of the water in the feed water supply tank. The time of weighing ash and refuse was likewise coincident with a "time of firing," though at less frequent intervals.

Sampling the Coal.—Samples of coal and ash could not be taken care of at the chemical laboratory until the morning following a

test, consequently, to avoid unaccounted-for changes in moisture content, the preliminary reducing, crushing and air drying of all samples were made in the boiler room.

In collecting the coal sample, two half shovelfuls of coal were taken for each 500 lb. charged during a test. The samples taken at each charge were at once crushed to less than quarter-inch size in a laboratory jaw crusher, and collected in a closely covered vessel. At the close of the test, a complete sample, weighing between 100 and 150 lb. or about 1 to 2 per cent of the total weight of coal fired during the test, depending upon the size of the coal, was carefully mixed and quartered down to about five pounds. From this, one kilogram was weighed out into a shallow pan for the determination of the moisture loss upon air drying.

Coal too wet for reducing at once in the jaw crusher was first sampled down to 10 kilograms, and this weight was given a preliminary drying in large pans set upon the grating surmounting the boiler. The temperature there ranged from 90° to 100° Fahr., and the drying was usually allowed to proceed over night. A record was then made of the loss, and the entire sample was reduced in the jaw crusher and further mixed and quartered down, and the air drying was concluded upon a 1000 gram sample, the total air drying loss in such case being given by the formula:

Moisture, per cent = $a + \frac{100-a}{100} b$; where a = the per cent loss in the preliminary drying and b = the per cent loss on the final sample.

A No. 80 Troemner's solution scale was used for weighing samples. This scale is very accurate and its construction allows the use of sample pans of any necessary size, the small sample pans used being 10 by 18 by 1 in. in depth, and the large pans 18 by 18 by 1 in.

In the final air-drying these pans were set away in a special sheet-iron oven, Fig. 20, the shelves of which are staggered to allow free circulation of air, which is induced by a Bunsen flame in the flue at the top. Since the air used for drying was not heated, the drying thus, at room temperature, required from three to four days, during which time the samples were weighed each day until the loss for the day preceding was less than 5 grams in 1000, when the samples were at once bottled in "Lightning" fruit jars and delivered to the chemical laboratory for final reducing and analysis.

Sampling the "Ash and Refuse."—The "ash and refuse" was removed from the ashpit, generally three or four times during a test. The contents of the car, weighing usually from 100 to 300 pounds, were dumped upon a smooth concrete floor and the clinker crushed with an iron tamp until all pieces were reduced to about $1\frac{1}{2}$ in. in size. The entire bulk was then mixed by twice shifting the pile, each shovelful being poured upon the center of the new heap so that the larger and heavier particles would, if possible, be evenly distributed. This bulk was then quartered, opposite quarters rejected and the tamping, mixing and quartering repeated until about 20 lb. remained. The particles were then reduced to about $\frac{1}{2}$ in. or less. This portion was then further reduced to $\frac{1}{4}$ in. or less by means of the jaw crusher, thoroughly mixed and a weight equivalent to 5 per cent of the original bulk preserved. This procedure was repeated for each quantity of "ash and refuse," and at the close of the test the aliquot samples thus obtained were thoroughly intermingled and quartered down to about two pounds, which was at once bottled for delivery to the chemical laboratory.

Feed Water.—The arrangement of the feed water system is shown in Fig. 19. The weighing tank has a capacity of 800 pounds, and is of the form commonly used for accurate measurement. It is provided with a small neck and an overflow. The tank is fitted with a 2-in. Lunkenheimer "Handy" gate valve on the supply pipe and a 3-in. similar valve on the discharge. It can be filled and emptied in about two minutes.

The number of tanks of feed water supplied to the boiler was recorded in the usual manner, recording both the time and number of the tank, and a check of the counts was maintained by means of a Bristol recording water-level gage connected to the 5000-lb. capacity supply tank. The temperature of the feed water was taken in the weighing tank before discharging. With the exception of tests 25 and 31, for which the pump was used, the boiler was fed by injector throughout the series. Three injectors, sizes 1, $1\frac{1}{4}$ and $1\frac{1}{2}$ in. were supplied so that a fairly steady feed was obtained for any rate of evaporation demanded from the boiler. The overflow from the injectors was returned to the supply tank, but since the temperature of the feed water was taken in the weighing tank, no correction for the weight or heat content of this overflow was necessary.

The total weight of water fed to the boiler, column 4, Table

32, is the weight of feed water by tank corrected for the following items:

1. Difference between the quantity of water weighed out and the quantity fed to the boiler; shown by the difference of the level of water in the supply tank at the start and close of the test.

2. Weight of feed water equivalent to the difference between the level of the water in the boiler at the start and close, with correction for the heat contained.

3. Water equivalent to the difference in the total heat of the boiler's water content at the start and close, due to difference between the steam pressures at those events.

4. Correction for leakage at the blow-off; pump leak, etc.

The total feed water weighed and the total correction applied, together with the data upon which this correction is based, are given in the water log, Table 31. The methods of arriving at the separate corrections follow:

1. Correction for level in supply tank: The supply tank was fitted with a delicate float gage which indicated the difference in level on a scale above. Each inch scale reading represented 145.5 lb. at 60° Fahr.

2. Correction for difference of water level in the boiler: It was endeavored to keep the water level within 3 to 6 inches, as shown on the water gage, middle gage being at 4.5 inches, and this was generally accomplished throughout the tests.

To allow correction for any differences of level at start and close, the boiler was carefully calibrated to each half inch on the glass. By this calibration, the water capacity of the boiler to middle gage is 17022 lb., and the average water capacity for each inch shown on the gage from $2\frac{1}{2}$ to $6\frac{1}{2}$ in. is 358.6 lb. at 62° Fahr. At 365° Fahr., corresponding to 150 lb. gage pressure, and further corrected for expansion of the boiler, one inch of water on the water gage represents 318 lb. average. This value was made the base for compensation for the thermal content of the weight represented by the difference in level in inches.

With more water in the boiler at the close than at the start, credit must be given for the heat required to raise the difference in weight from feed water to steam temperature. With the conditions reversed, credit must be given for evaporating the difference but not with heating it to steam temperature.

The correction to be applied to the feed water for each inch difference in level in the gage is given by the formula,

$$318 \times \left\{ 1 - \frac{q - q_1}{q - q_1 + \left(\frac{100 - r}{100} \right) r} \right\}$$

where q = the heat of the liquid at steam temperature, q_1 = the heat of the liquid at feed water temperature, r = the heat of vaporization, and x = the per cent of moisture in the steam. The latter may be neglected in the calculations.

The corrections per inch of gage reading used in the test calculations were obtained from a chart based upon the above formula.

It will be seen that since the feed water temperature was from 55° to 60° Fahr. and the pressure from 145 to 155 pounds gage, the correction applied to the total weight of water fed was about constant at 233 lb. per inch of water gage difference.

3. Feed water correction for difference in steam pressure at start and close: This correction is a minor one, amounting to but 5.8 lb. of feed water to be added or subtracted per pound difference in steam pressure within the range of the experiments.

4. Correction for leakage at the blow-off valves: The lower blow-off valve began leaking during test No. 20 and continued until test No. 27, before repairs could be made. The leakage was conducted into a weighed tank of cold water and the weight of feed water to be subtracted in correction calculated by the formula:

$$\text{Correction} = (\text{Wt. of leakage}) \times \left\{ 1 - \frac{q - q_1}{q - q_1 + r} \right\}$$

The symbols have the usual significance. Peabody's steam tables were used throughout for the thermal properties.

Character of the Feed Water.—The water used in the test boiler and in the central heating plant comes from 125-ft. wells on the University grounds. The water is characterized by the presence of free sodium carbonate in amount greater than is necessary to satisfy any sulphates present, and consequently is absolutely non-scale forming.

Water of this character is found at a depth varying from 125 to 165 feet throughout an area of about 4000 sq. miles centering

about the University. It is also found in several other sections in Illinois at depths varying from 400 to 850 ft. A description of this water has been given recently by Professor S. W. Parr.* The normal amount of free alkali is about 5 grains per gallon.

During the progress of the tests, the writer personally inspected the boiler tubes on four occasions but no scale whatever was found. At the close of the series the tubes were as clean as when the boiler was first fired, save for the light coating of sludge dust which could be brushed away with the finger.

The Water-Back.—To avoid unnecessarily complicating the feed water system, the cooling water for the water-back was wasted to the drain. A measure of this water was kept by means of a carefully calibrated Breslau water meter placed in the inlet pipe, and to insure approximately a steady rate of flow through the meter, the temperature of the outflow was normally adjusted to a temperature from 80 to 100° Fahr., so that some variation in the range of temperature was allowable without complicating the measurements by too frequent adjustments.

Temperatures of the inflow and outflow and the meter's reading were taken at the regular intervals, and the amount of heat carried away by the cooling water was computed by taking the product of the total weight of water used during the test, corrected to agree with the calibration of the meter, and the average difference in temperature. The fact that an average was used here in place of the true mean introduces but a negligible error since the per cent loss of heat is in itself a relatively small item.

It may be said that the water-back can not be considered as being under practical test, but if one wishes to compute the amount of cooling water that would be required for various temperatures of the outflow, it may readily be done from the data given in Table 30.

The use of the adjustable water-back in the experimental plant has given the advantage of uniform conditions for fuels of varying character and ash content. No assumption is made, however, as to whether or not the adjustable water-back results in an economy over other methods of controlling the air leakage.

Compensated Water Items.—It will be noted that the tabulated water items and dependent items are expressed in two ways. Un-

* "Some Notes on the Service Waters of a Railway System," Jour. of the American Chemical Society, Vol. XXVIII, 5, 640, May, 1906.

der the regular A. S. M. E. code numbers are given the values obtained by actual performance, (designated "performance" in the headings). In adjacent columns and designated by the same code numbers, but with a decimal suffix, these items are raised to values which, it must be assumed, would have resulted had the water-back been of a stationary type in which the circulation water is taken from and returned to the boiler. These items are designated in the table headings "compensated for water-back" in brief for "compensated for the heat lost on account of the water-back". They are introduced for the purpose of eliminating variations. In making the compensations, the percentage loss of heat in the cooling water to the total heat of the fuel consumed has been added directly to the "boiler and furnace" efficiency per cent numbers, and the related water items and the numbers for Item 73 raised by the factor $\frac{\text{Item 72} + \text{Heat loss per cent.}}{\text{Item 72}}$.

Details of the calculations for different items are shown on pages 109 to 120.

Care of the Boiler.—Soot and dust are removed from the heating surface of the Heine boiler by means of a steam or air nozzle inserted through hollow stay bolts in the front and rear water legs. The nozzle used consists of a long pipe perforated at the end by a number of radial holes.

The surfaces were carefully cleaned, preceding each test, with an air blast of from 70 to 100 lb. pressure, blowing through each stay bolt in both front and rear legs and inserting the pipe the full length of the tubes. Several inspections of the tube surfaces showed that this treatment given each day maintained a remarkably clean surface, and since the furnace operated with but occasional traces of smoke, opportunity for coatings of tenacious character to form was entirely absent.

Starting and Stopping the Tests.—Running start and stop was necessarily made. With the chain grate the amount of ash upon the grate is practically constant, the depth of fuel entering the furnace is fixed by the gate opening and is not disturbed by motion of the grate. These circumstances are favorable to a running start yet the possibility of serious error is not obviated. Variation in weight of fuel upon the chain grate at start and close of the test may occur from one or all of several causes occurring or operating for a period required to displace the grate one effective

grate length just preceding either event. These are:

1. Difference in actual length of fuel bed.
2. Irregularity in speed of grate travel.
3. Variations in air supply.
4. Difference in the relative amounts of fine-sized fuel falling through the grate.
5. Differences occasioned by irregular attention to condition of the fuel bed.
6. Difference in clinkering or caking.

It is found that to bring the fuel bed to the same length just at the time of starting and stopping is not sufficient for accuracy. If it is necessary to quickly close up a short fuel bed to bring this about, the conditions are bad. One linear foot of grate travel carries into the furnace from 70 to 150 lb. of coal, depending upon the width of grate and depth of gate opening. Sudden changes of grate speed, consequently, produce excess or deficiency from the normal amount of fuel which should be upon the grate. Ideal conditions demand uniform rate of combustion and fuel bed length during the periods of time that determine the weight of fuel that will be upon the grate.

Variations due to these factors were avoided as far as possible by operating the grate under assigned test conditions for a period of from 30 minutes to 1 hour just preceding the start. The principal conditions observed were regularity of grate travel, and area of fuel bed and a constant "normal" draft pressure (see definitions, page 12).

For those tests in which the fuel clinkered more or less seriously, it was of course impossible to assure a uniform rate of combustion, and satisfactory agreement between starting and stopping conditions was more difficult to obtain. This difficulty was experienced with the fuel 5.1006 W. Satisfactory agreement was also difficult to obtain with the fine-sized coals. For several of the tests of fine sizes the furnace was operated under test conditions from 3 to 4 hours before acceptable conditions for starting were obtained.

Preceding all tests, the fireman operated the furnace as nearly as possible under assigned test conditions for two hours before the arrival of the regular observers, a check on the regulation during this period being maintained by means of recording gages for draft pressure and for temperature of the flue gases.

As an additional check on the starting conditions for all tests following test No. 27, the regular water readings were taken for 1 hour preceding the start and the load computed. If proper conditions of the furnace or load were not reached, the preliminary run was continued, taking readings as in the test proper. After one or two tests on each grade of coal, satisfactory starting conditions were usually obtained without trouble. The grate once adjusted to the requirements of the fuel and draft, closing conditions were usually readily obtained.

The fire was started each morning at 5 o'clock from a heavy banked fire, and was under full fire from $1\frac{1}{2}$ to 3 hours preceding all tests. The fuel to be tested was used during this period in order that the furnace and setting wall would be heated only to the normal temperature for that fuel; except in a few tests of the No. 5 coal, screenings were used for the first hour to bring the furnace to temperature more quickly. A check on the temperature of the furnace walls was obtained by means of thermometers slightly imbedded in the surface. The indications of these thermometers at all times varied more from drafts of air through the boiler room than from any difference of temperature within the furnace.

II. OBSERVED AND CALCULATED RESULTS OF TESTS

In the calculation of the results given in the tables following, the methods set forth in the code for boiler testing of the American Society of Mechanical Engineers, wherever they apply, have been followed in detail. Those items are tabulated under the regular code item numbers, and have the usual significance. Additional items are indicated by letters or by decimal suffixes to the usual code numbers.

In order to collect the results into compact and convenient tables and to provide space for additional items, it has been necessary in some cases to arrange the items in a different order from that usually followed in the A. S. M. E. code. For example, the items under the sub-head "water per hour" follow directly after "fuel per hour" in Table 33; the average steam pressure will be found under the heading "steam" in Table 30; draft pressures and air temperatures will be found under the headings "air" in Table 36; and the analysis of the flue gases and the per cent of smoke observed will be found in the same table. Other items

which are displaced from the arrangement of the A. S. M. E. code are "size of coal" and "thickness of fuel bed" Table 28; "temperature of the feed water" Table 32; "analysis of ash and refuse" Table 29; and "calorific value of the fuel" Table 39. In the following summary, the items are taken up in the order in which they appear in the tables.

TABLE 28. Principal Conditions—In this table those conditions which have the greatest effect upon the results of the tests are given. The items of Table 40 should also be consulted in a comparison of test results.

Column 1. Test number for this series.

Column 2. Laboratory file number. This number appears in each of the tables in the report and should serve as a convenient cross index to the fuel tested. The first part of the number refers to the files of the laboratory. All boiler or fuel tests made at the Engineering Experiment Station are given a general number and filed in that order regardless of the test series. General numbers not included are tests in other series, central heating plant tests or tests with house-heating boilers. The second part of the number is the fuel symbol, an explanation of which will be found on page 4.

Item 2. Duration of trial. The total time reduced to decimal number.

Commercial boiler trials are usually run for a ten hour period, the idea being that within that period sufficient total weight of fuel will be fired to minimize a reasonable and unavoidable error in judging the conditions and weight of fuel upon the grate at the start and close. In the adoption of a shorter trial period for this series, it is not intended to advocate any change in existing practice. Satisfactory starting and closing conditions with the chain grate, since they must be running conditions, are often and especially with non-uniform coal, much more difficult to obtain than for the plain grate using the "alternate method" of the American Society of Mechanical Engineers.

In these tests the duration of the trial has been wholly determined by the conditions under which the start and stop could be made, conditions which were in most cases favored by the superior and uniform grades of coal tested. It was usually endeavored

to prolong the trial until 200 lb. of coal had been fired per square foot of grate surface. This, however, was not always accomplished; a trial was to be run each day, the time of several men had to be regulated, and time allowed for the care of the boiler and the operation of the furnace under suitable conditions preliminary to the start.

The majority of the tests of short duration or in which less than a total of 200 lb. of coal was burned per square foot of grate surface, are duplicated on the same lot of coal. A comparison of the conditions and results for these duplicates is of interest. Short duration in tests 15, 44 and 64 was due to lack of sufficient supply of test coal for a longer period; however, the tests were run under favorable conditions. The conditions of test 15 duplicate those of test 14. The conditions under which tests 44 and 64 were made are not exactly duplicated by other tests. Test 8 was closed suddenly because of the blowing out of a gasket in the rear water leg. The close of the test was accepted as the time of the last coincident coal, ash and water reading; comparisons show the results to be good.

Item 23, Column 5. Size of coal.

Item 23, Column 6. Condition of coal.

Item 81, Thickness of fuel bed, inches. This is taken as the depth of the gate opening. The average thickness of the fuel bed upon the chain grate is, of course, less than this, but on account of the progressive combustion, this average can not be judged. However, a knowledge of the average would be of no more practical value than a record of the gate opening which can always be duplicated.

Item 13.1. Draft pressure in the furnace (assigned). This is the normal draft pressure assigned for the test. The averages of observed draft pressures are given in Table 30.

Column 9. Furnace control.

Column 10. Total coal fired per sq. ft. of grate area, pounds =

Item 25 ÷ 38.2.

TABLE 29. Coal and Ash—This table contains all items necessary for the calculation of the combustible consumed except the per cent of ash in the dry coal, Item 42, Table 38.

Item 25. Total weight of coal fired, pounds.

Item 26. Percentage of moisture in the coal as fired, pounds. See Item 34, Table 37.

Item 27. Total weight of dry coal fired, pounds = Item 25 $\times$ (1 — Item 26).

The term "fired" for obvious reasons is introduced here in place of the term "consumed" as used in the A. S. M. E. code. The term "consumed" is used in this report only in connection with that portion of the fuel or combustible which has been delivered beyond the bridge wall in the form of gases or carbon, i. e., the fuel or combustible fired minus that portion accounted for in the "ash and refuse".

Item 28. Total weight of dry ash and refuse, pounds.

Item 30. Total weight of combustible consumed. This is equal to the total weight of combustible (ash free dry coal) fired minus the weight of carbon in the "ash and refuse" = Item 27 $\times$ (1 — Item 42) — (Item 28 $\times$ Item 44).

Item 31. Per cent of "ash and refuse" referred to dry coal = Item 28 $\div$ Item 27.

Item 44. Per cent of carbon in dry "ash and refuse." By chemical analysis.

Item 45. Per cent of earthy matter in dry "ash and refuse". By chemical analysis.

Item 30.1. Total weight of dry coal minus the total weight of "ash and refuse", pounds = Item 27 — Item 38.

This item is given as a rough check on Item 30. Item 30.1 will generally be greater than Item 30 by a weight equal to the weight of ash carried beyond the bridge wall or collected on the walls of the furnace, though with well-sized clean coal the difference is usually small. Where Item 30.1 is the greater, it is usually due to increase in Item 28 from melting of the slag and fine ash which has accumulated on the face of the furnace walls and bridge wall during preceding operations. No error is introduced in Item 30 because of these gains or losses of ash, since the calculation is based upon the chemical analysis of the ash and refuse. Also any coal particles carried beyond the bridge wall settle in the combustion chamber and are completely burned in this furnace

TABLE 30. Steam and the Water-Back.—This table contains all of the steam and water-back data and factors.

Steam:—

Column 3. Barometric pressure in lb. per sq. in.

Item 11. Average steam pressure by gage. The test boiler discharged its steam directly into a branch main of the central heating and power station, the normal pressure of which ranged between 130 and 145 pounds. The test boiler pressure was maintained at approximately 150 lb. gage by regulating the main steam valve. This was attended to by the water observer. An extra steam gage located below the valve and in view from the lower deck facilitated the regulation.

The steam pressures tabulated are the averages from Bristol recording gage charts. The steam pressures recorded at start and close, Table 31, are the indications of a standard gage of the Bourdon type. Both the recording and the standard gage were mounted on the same gage board and the two were compared at the start and close of each test. Both instruments were frequently checked by calibration.

Item 11.1. Absolute steam pressure = Item 11 + Column 3.

Item 54. Percentage of moisture in the steam. During the earlier portion of the tests, the moisture carried by the steam was determined by means of a Carpenter separating calorimeter. The six-inch vertical steam riser was well lagged; the sampling nipple was of standard design and located about 3 ft. above the boiler. At 4½ ft. above the boiler the riser ends in an ell connecting a special main 20 ft. in length. This short main connects with the branch main of the central heating plant by a down connection 10 ft. in length. However, to insure further that no condensation from the 20 ft. horizontal could return to the boiler, it was given a positive slope of 1 in. in 10 ft. The velocity of the steam in the riser is about 35 ft. per second when the boiler is delivering 210 H. P. The steam from the separating calorimeter was condensed in a special small worm condenser, the accuracy of the weight delivered by the orifice in no case being accepted.

This calorimeter was used up to test No. 24 when two other calorimeters were added for the purpose of checking. One of these was a throttling calorimeter of standard design; the other a very large special separating calorimeter so constructed that the orifice could be changed to different sizes as desired. It was found

that the throttling calorimeter gave approximately constant moisture readings. A series of experiments carried out at the same time by means of the large separating calorimeter, in which the total sample of steam drawn was gradually increased until the radiation from the well lagged calorimeter became negligible, confirmed the indications of the throttling calorimeter so that in the tests following test No. 23 the indications given by the throttling calorimeter were accepted.

It was found that a line drawn through all of the percentages thus obtained, the variation being from 0.5 to 0.7 of one per cent, was a constant at about 0.57. Since the radiation correction for the throttling calorimeter varies between 0.1 and 0.3 of one per cent it was concluded that the moisture content of the steam was constant at about 0.57 per cent, and this value was used in all tests following test No. 31, with the exception of tests 40, 41 and 42 where the variations were slightly in excess of the usual variation, as was the case likewise in the tests 24 to 30.

Item 56. Factor for correction for quality of steam =

$$1 - \left\{ \frac{\text{Item 54}}{100} \times \frac{q - q_1}{r + q - q_1} \right\} \quad \text{where } q = \text{the heat}$$

of the liquid at the steam temperature, q_1 = the heat of the liquid at feed water temperature, and r = the heat of evaporation at steam pressure. Values for q , q_1 and r were taken from Peabody's steam tables and a curve constructed from which the factors were taken for the computations.

The Water-Back. See page 82.

Item a. Total weight of cooling water used.

Item b. Temperature of inflow, average, degrees Fahrenheit.

Item c. Temperature of outflow, average, degrees Fahrenheit.

Item d. Ratio of the heat lost to the water-back to the total heat of the fuel consumed = Item a (Item c—Item b) ÷ (Item 30 × Item 51).

Item e. Water equivalent correction factor for the heat lost to the water-back = Item 72.1 ÷ Item 72. See page 106.

TABLE 31. Water Log Data—An explanation of this table together with the means of obtaining the weight of feed water, also the necessary corrections applied, are given on page 102.

TABLE 32. Total Water—All of the total water items are contained in this table.

Item 20. Temperature of feed water entering the boiler, degrees F.
See above.

Item 57. Total weight of water fed to the boiler, pounds.
See above.

Item 58. Equivalent water fed to the boiler from and at 212° F., pounds = Item 57 × Item 60.

Item 59. Water actually evaporated corrected for quality of steam, pounds = Item 57 × Item 56.

Item 60. Factor of evaporation = $(q - q_1 + r) \div 965.8$.

The thermal quantities were taken from Peabody's steam tables.

Item 61. Equivalent water evaporated into dry steam from and at 212° F., (performance) pounds = Item 59 × Item 60.

Item 61.1. Equivalent water evaporated into dry steam from and at 212° F., compensated for water-back loss, pounds = Item e × Item 61.

Item f. Total loss of equivalent evaporation charged against the water-back = Item 61.1 — Item 61.

TABLE 33. Fuel and Water per Hour—All fuel and water items calculated to the basis of one hour are collected under this head.

Fuel per Hour:

Item 46. Dry fuel fired per hour, pounds, = Item 27 ÷ Item 2.

Item 47. Combustible consumed per hour, pounds, = Item 30 ÷ Item 2.

Item 48. Dry coal fired per square foot of grate surface per hour, pounds = Item 46 ÷ 38.2.

Item 49. Combustible consumed per hour per square foot of water heating surface, pounds, = Item 47 ÷ 2027.

Water per Hour:

Item 62. Water evaporated per hour, corrected for quality of steam, pounds, = Item 59 ÷ Item 2.

Item 63. Equivalent evaporation per hour from and at 212° F. pounds, = Item 61 ÷ Item 2.

Item 64. Equivalent evaporation per hour from and at 212° F. per square foot of water heating surface, pounds, = Item 63 ÷ 2027.

Item 63.1. Equivalent evaporation per hour from and at 212° F. compensated for the water-back loss, pounds, = Item 63 × Item e.

Item 64.1. Equivalent evaporation per hour from and at 212° F. per square foot of water-heating surface, compensated for the water-back loss, pounds = Item 64 × Item e.

TABLE 34. Horse-power and Economic Results

Item 65. Horse-power developed = Item 63 ÷ 34.5.

Item 67. Percentage of builders' rated horse-power developed, per cent, = Item 65 ÷ 210.

Items 65 and 67 compensated for the water-back loss are given in Table 5 to 14.

Economic Results by Actual Performance:

Item 68. Water apparently evaporated under actual conditions per pound of coal as fired, pounds, = Item 57 ÷ Item 25.

Item 69. Equivalent evaporation from and at 212° per pound of coal as fired, pounds, = Item 61 ÷ Item 25.

Item 70. Equivalent evaporation from and at 212° per pound of dry coal fired, pounds, = Item 61 ÷ Item 67.

Item 71. Equivalent evaporation from and at 212° per pound of combustible consumed, pounds, = Item 61 ÷ Item 30.

Economic Results Compensated for Water-Back Loss:

Item 68.1. Water apparently evaporated per pound of coal as fired, pounds = Item 68 × Item e.

Item 69.1. Equivalent evaporation from and at 212° per pound of coal as fired, pounds = Item 69 × Item e.

Item 70.1. Equivalent evaporation from and at 212° per pound of dry coal fired, pounds = Item 70 × Item e.

Item 71.1. Equivalent evaporation from and at 212° F. per pound of combustible consumed, pounds = Item 71 × Item e.

TABLE 35. Efficiency and cost of Evaporation—.

Item 72. Efficiency of the "Boiler and Furnace" = (Item 71 × 965.8) ÷ Item 51.

Item 73. The over-all efficiency = (Item 70 × 965.8) ÷ Item 50.

Item 72.1. Efficiency of the "Boiler and Furnace", compensated for water-back loss = Item 72 + Item d. See Table 30 for Item d.

Item 73.1. Over-all efficiency, compensated for water-back loss =
Item 73 $\times$ Item e.

Cost of Evaporation:

Item 74. Cost of coal per ton of 2000 lb. delivered in boiler room.
This is arbitrarily taken as one dollar.

Item 75. Cost of coal for evaporating 1000 lbs. of water under observed conditions, dollars, = $0.5 \div$ Item 68.1.

Item 76. Cost of coal used for evaporating 1000 lb. of water from and at 212 degrees, dollars, = $0.5 \div$ Item 69.1

TABLE 36. Air and Flue Gases. This table contains the items relating to the air supply and flue gases including the smoke observations.

Item 12. Average draft pressure between damper and boiler, in. of water. This was taken by means of an Ellison differential draft gage, the point of observation for tests following test 28 being at hole 12, see Fig. 21, page 85. For test preceding test 29 the observation was taken at the turn in the breeching.

Item 13. Average draft pressure in furnace, in. of water. Taken by means of an Ellison differential draft gage of $\frac{1}{2}$ in. range, graduated to $\frac{1}{100}$ of 1 in. For the majority of the tests readings were taken at two points, 21 and 22, Fig. 21 and 22, the gages being connected up differentially to holes 27 and 26, respectively, so that the averages tabulated are actual net pressures on the fuel bed.

Item 15. Average temperature of external air, degrees Fahrenheit, obtained from the record of a Bristol recording thermometer.

Item 16. Average temperature of boiler room, $^{\circ}F$, obtained from the record of a Bristol recording thermometer.

Item 21. Average temperature of the escaping flue gases: $F.^{\circ}$
 Readings for the flue gas temperatures during tests 1 to 27 were taken by means of a single high grade mercury thermometer inserted at the base of the breeching in a position which was supposed to be average. The data are retained in the table but they are unreliable. For tests 28 to 37 the temperature data are the average of three high grade Jena borosilicate glass thermometers located in the sampling section above the mixing baffles. Fig. 23. In the tests following test 37 temperature measurements

were taken by means of five copper-constantan thermo-couples distributed in the sampling section.

Items 85, 86, and 88. Analysis of dry flue gases. For tests No. 1 to 27 the gas samples were drawn from a single tube, extending centrally across the base of the breeching. This tube was made up of $\frac{1}{2}$ -in. pipe capped at one end and perforated with three rows of $\frac{1}{8}$ -in. holes spaced 3 in. apart. The results from the analyses of samples taken from this tube are of uncertain accuracy for the reasons set forth on page 88, and with but few exceptions the tabulated percentages of carbon dioxide for those tests are probably too high. This was recognized at the time the tests were in progress, and for that reason it was considered useless to make more complete analyses until time should permit devising and installing improved means for taking the sample. During the temporary interruption of the work which occurred between the tests 27 and 28, opportunity permitted the introduction of the sampling arrangement, previously described, and all subsequent gas samples for the series were taken under those improved conditions.

The sampling tube or tubes in both types of samplers were connected with the sampling bench by a $\frac{1}{4}$ -in. lead tubing, through which a steady stream of gas was kept flowing by means of a larger sized Richards laboratory ejector. The sample for analysis was drawn from a tee connection in this tube. The usual arrangement of one-gallon side-necked aspirator bottles was used for collecting the sample and an average sample collected for each half hour during the test. In some of the earlier tests the samples were drawn for a longer period. Distilled water saturated with the flue gas was used in the collecting vessels.

The analyses throughout were made by means of an Orsat apparatus provided with a 100 cc. water jacketed burette with 25 cc. tube of special wide graduation, and the readings taken subsequently corrected to the true calibration of the burette, including a correction for the gas volume contained in the capillary tube between the 100 cc. mark and the drop tubes, the total correction necessary being between 0.1 and 0.2 of 1 cc. representing a percentage correction of about the same magnitude in the observed percentages of carbon dioxide and oxygen.

Item 77. Smoke observations—Ringelmann's numbers. The observations taken were recorded in No. 0, $\frac{1}{2}$, 1, 2, etc., no

attempt being made to judge shades varying between. The tabulated values, however, being the time average of all readings, result in fractional values. These should be interpreted as being simply greater or less than Ringelmann Chart No. 1 or No. 2 as the case may be, for example, test No. 44 shows 0.21 smoke. That is, the average smoke reading for this test was less than No. 1 Ringelmann.

To summarize these readings for the series; three tests show No. 1 smoke, 13 tests what may be called, on the average, a faint haze, and for the remainder, 48 tests, one could not tell from observation of the stack, that the plant was in operation.

Chemical Analyses:

The chemical analyses of the coal and of the "ash and refuse" were made in the University chemical laboratories, under the direction of Professor S. W. Parr.

The data obtained from the analyses were more elaborate than apply directly to the needs of this report, and, no doubt, will contribute to the accumulation of available data for a more general study of the chemical and physical properties of Illinois coal, a problem which is receiving the attention of Professor Parr in connection with the State Geological Survey. All chemical analyses were made in duplicate and in case of an occasional disagreement, the results were checked by a third determination. The results reported by the chemical laboratory were the average of two closely agreeing analyses.

The methods of analysis followed were: total moisture equals the per cent loss upon air drying plus the loss in drying in an air oven at 105° C.; proximate analyses, following the methods recommended by the Committee on coal analysis of the American Chemical Society*; sulphur by gravimetric method after fusion with sodium peroxide in the Parr calorimeter, nitrogen by the Kjeldahl method; total carbon and hydrogen by the usual combustion train method, carbon in the "ash and refuse" by difference after determining the moisture and ash contained, and the calorific value of the coal by means of a platinum lined Mahler-Atwater calorimeter.

Determinations regularly made upon each test sample of coal were moisture, ash, sulphur, nitrogen and the calorific value, and upon the "ash and refuse" sample, moisture, ash and carbon.

* Jour. Amer. Chem. Society, Vol. XXI, p. 1130.

Complete proximate and ultimate analyses were made upon two samples from each carload of coal tested. One of those samples was a regular test sample, the second a composite sample made up from the regular analytical samples in portions of each representing by weights the separate original weights of coal sampled.

These composite analyses are presented on pages 5 to 6 in connection with the description of the coal used.

Where complete analyses have been made of individual test samples, they are given in Tables 37, 38 and 39. Figures set in regular type indicate results from analyses of the individual test samples. The italicised figures are calculated values based upon the percentages of fixed carbon and volatile matter, total carbon, hydrogen and oxygen found in the composite sample and the percentages of moisture, ash, sulphur, and nitrogen found in the individual test samples, the principle being that the average chemical character of the "combustible" portion of the coal excluding sulphur will be approximately constant throughout the car. How nearly this was true will be seen by comparison of the values calculated for the combustible composition from the composite analyses, and the similar values for the individual samples, Table 39, making allowance in the comparison for any variation which occurs in the percentages of sulphur and nitrogen.

The method of calculating these figures is given below.

In these tables both analytical and calculated results for coal as fired or for moisture-free coal are given the regular A. S. M. E. code item numbers, while the similar items computed to the basis of combustible are distinguished by a decimal 1, suffixed. Similarly, to distinguish them in the formulas which follow, items relating to determinations made upon the composite samples are indicated by suffixing a decimal 2 to the regular A. S. M. E. code numbers.

TABLE 37. Proximate Analyses:

Item 32. Fixed carbon = $\text{Item } 32.2 \times \frac{100 - (\text{Item } 34 + \text{Item } 35)}{\text{Item } 32.2 + \text{Item } 33.2}$
 = $\text{Item } 32.2 \times k$ (a constant). Item 34 and 35 are those values given in the same table. Items 32.2 and 33.2 may be taken from either Table 2, 3 or 4. Those from table 2 were used.

Item 33. Volatile matter = $\text{Item } 33.2 \times k$.

TABLE 38. Ultimate Analyses of Moisture Free Coal
Item 37.

$Total\ carbon = Item\ 37.2 \times \frac{100 - Item\ 40 + Item\ 41 + Item\ 42}{Item\ 37.2 + Item\ 38.2 + Item\ 39.2}$
 $= Item\ 37.2 \times m.$ Item 40, 41 and 42 are those values given in the same table. Items 37.2, 38.2 and 39.2 may be taken from either Table 2, 3 or 4. Those from Table 2 were used.

Item 38. Hydrogen = Item 38.2 $\times m.$

Item 39. Oxygen = Item 39.2 $\times m.$

TABLE 39. Calorific Value and Ultimate Analyses of Combustible:

Item 59 and 51, Calorific values, B. t. u.

Item 37.1, 38.1, 39.1, 40.1 and 41.1 are calculated by multiplying the items of Table 38 by the factor $\frac{100}{100 - Item\ 42}$

TABLE 40. Furnace Conditions:

An explanation of the items contained in this table has been given on page 92.

TABLE 28 PRINCIPAL CONDITIONS

No.	Laboratory File No.	Date of Trial	Duration	Principal Conditions					
				Size of Coal (Commercial)	Condition of Coal	Thickness of Fuel Bed	Draft Pressure in Furnace Assigned	Furnace Control	Total Coal Fired per Sq. Ft. of Grate Area
1	2	3	4	5	6	7	8	9	10
	Code Item	1	2	23	23	81	13		
			Hr.	In.		In.	In.		Lb.
1	21-4.0703 W	Dec. 7, '06	8.17	$\frac{3}{8}$ - $\frac{3}{8}$	Washed	6	0.20		301
2	23- "	Dec. 10, '06	6.08	" "	"	5	0.16		209
3	24- "	Dec. 11, '06	8.17	" "	"	4	0.12		236
4	25- "	Dec. 12, '06	7.97	" "	"	7	0.25		291
5	26- "	Dec. 13, '06	7.63	" "	"	4	0.10		262
6	30-5.0802 W	Dec. 18, '06	8.00	$\frac{3}{4}$ - $\frac{1}{4}$	"	4	0.10		209
7	31- "	Dec. 19, '06	7.87	" "	"	4	0.12		223
8	32- "	Dec. 20, '06	5.55	" "	"	5	0.11		144
9	34- "	Jan. 10, '07	7.25	" "	"	6	0.14		196
10	35- "	Jan. 11, '07	8.13	" "	"	7	0.17		209
11	36- "	Jan. 12, '07	8.08	" "	"	6	0.16		209
12	37-5.0200 W	Jan. 14, '07	6.43	$\frac{1}{4}$ -0	"	5	0.29		196
13	39- "	Jan. 17, '07	7.93	" "	"	6	0.39		249
14	40- "	Jan. 18, '07	7.78	" "	"	6	0.45		249
15	41- "	Jan. 21, '07	5.70	" "	"	4	0.23		209
16	42- "	Jan. 22, '07	5.10	" "	"	4	0.29		183
17	43-4.0700 W	Jan. 23, '07	8.15	$\frac{3}{8}$ -0	"	5	0.14		236
18	44- "	Jan. 24, '07	8.07	" "	"	5	0.14		236
19	45- "	Jan. 25, '07	8.08	" "	"	4	0.12		236
20	46- "	Jan. 26, '07	7.90	" "	"	6	0.16		236
21	47-6.0402 W	Jan. 28, '07	8.32	$\frac{3}{4}$ - $\frac{1}{4}$	"	7	0.15		209
22	48- "	Jan. 29, '07	8.25	" "	"	6	0.14		196
23	49- "	Jan. 30, '07	8.22	" "	"	5	0.10		183
24	50- "	Jan. 31, '07	8.32	" "	"	4	0.90		209
25	51-5.1610 W	Feb. 1, '07	8.40	$1\frac{3}{4}$ -1	"	5	0.13		196
26	52- "	Feb. 2, '07	8.12	" "	"	6	0.13		209
27	53-6.0402 W	Feb. 4, '07	8.40	$\frac{3}{4}$ - $\frac{1}{4}$	"	6	0.13		209
28	93-5.1610 W	Apr. 26, '07	8.22	$1\frac{3}{4}$ -1	"	7	0.15		196
29	94- "	Apr. 27, '07	7.82	" "	"	6	0.13		183
30	95- "	Apr. 29, '07	8.07	" "	"	5	0.11		196
31	96-7.1610-	Apr. 30, '07	8.25	" "	Unwashed	5	0.10		196
32	97- "	May 1, '07	7.20	" "	"	6	0.13		170

See Page 21, for Method of Furnace Control

TABLE 28 PRINCIPAL CONDITIONS (*Concluded*)

No.	Laboratory File No.	Date of Trial	Duration	Principal Conditions					
				Size of Coal (Commercial)	Condition of Coal	Thickness of Fuel Bed	Draft Pressure in Furnace Assigned	Furnace Control	Total Coal Fired per Sq. Ft. of Grate Area
1	2	3	4	5	6	7	8	9	10
	Code Item	1	2	23	23	81	13		
			Hr.	In.		In.	In.		Lb.
33	98-7.1610-	May 2, '07	8.38	1 $\frac{3}{4}$ -1	Unwashed	7	0.15		209
34	99- "	May 3, '07	8.07	"	"	6	0.12		209
35	100- "	May 4, '07	6.80	"	"	6	0.17		196
36	101- "	May 6, '07	8.10	"	"	6	0.20		262
37	102-5.1006 W	May 7, '07	6.05	1 - $\frac{3}{4}$	Washed	5	0.10		144
38	104- "	May 8, '07	8.18	"	"	5	0.09		183
39	107- "	May 9, '07	8.10	"	"	6	0.12		183
40	109- "	May 10, '07	7.82	"	"	7	0.15		183
41	110- "	May 11, '07	7.55	"	"	5	0.15		223
42	112- "	May 13, '07	7.85	"	"	5	0.10		157
43	113- "	May 14, '07	7.30	"	"	6	0.19		223
44	114- "	May 15, '07	4.82	"	"	6	0.25		183
45	115-6.0200 W	May 16, '07	8.02	$\frac{1}{4}$ -0	"	4	0.23		157
46	116- "	May 17, '07	6.00	"	"	6	0.40		132
47	117- "	May 18, '07	6.68	"	"	6	0.43		165
48	118- "	May 20, '07	7.95	"	"	6	0.38		196
49	119- "	May 21, '07	7.38	"	"	6	0.32		144
50	120- "	May 22, '07	8.17	"	"	5	0.32		196
51	121- "	May 23, '07	8.00	"	"	5	0.37		196
52	122- "	May 24, '07	8.42	"	"	5	0.38		223
53	124-4.0300 W	May 27, '07	7.87	$\frac{3}{8}$ -0	"	5	0.34		262
54	125- "	May 28, '07	8.12	"	"	5	0.30		223
55	126- "	May 29, '07	6.00	"	"	5	0.38		200
56	127- "	May 30, '07	7.02	"	"	5	0.40		246
57	128-4.0703 W	May 31, '07	8.27	$\frac{7}{8}$ - $\frac{3}{8}$	"	5	0.13		236
58	129- "	June 1, '07	6.80	"	"	5	0.12		204
59	130- "	June 3, '07	7.25	"	"	5	0.10		157
60	131- "	June 4, '07	8.15	"	"	5	0.12		209
61	132- "	June 5, '07	8.73	"	"	5	0.14		241
62	133- "	June 6, '07	7.95	"	"	5	0.18		275
63	134- "	June 7, '07	7.37	"	"	5	0.16		251
64	135- "	June 8, '07	7.00	"	"	5	0.06		120

See Page 21, for Method of Furnace Control

TABLE 29 COAL AND ASH

No.	Laboratory File No.	Total Coal and Ash							Analyses of Ash and Refuse	
		Weight of Coal as Fired	Percentage of Moisture in Coal	Total Weight of Dry Coal Fired	Total Ash and Refuse	Total Dry Coal Minus Ash and Refuse	Total Combustible Consumed	Percent of Ash and Refuse Referred to Dry Coal	Carbon	Earthy Matter
		3	4	5	6	7	8	9	10	11
1	2	25	26	27	28	30.1	30	31	44	45
		Lb.	%	Lb.	Lb.	Lb.	Lb.	%	%	%
1	21-4.0703 W	11500	18.38	9386	1386	8000	7878	14.80	45.15	54.85
2	23- ..	8000	18.63	6510	737	5773	5698	11.32	24.13	75.87
3	24- ..	9000	17.35	7438	911	6527	6407	12.25	29.66	70.34
4	25- ..	11100	19.11	8979	1040	7939	7849	11.58	23.48	76.52
5	26- ..	10000	18.71	8129	1046	7083	6965	12.87	28.13	73.87
6	30-5.6602 W	8000	12.24	7021	861	6160	6028	12.25	21.03	78.97
7	31- ..	8590	13.15	7382	999	6383	6277	13.53	34.98	65.02
8	32- ..	5500	12.48	4814	560	4254	4178	11.63	19.90	80.10
9	34- ..	7500	13.13	6515	686	5829	5723	10.53	14.75	85.25
10	35- ..	8000	11.30	7096	695	6401	6255	9.79	15.81	84.19
11	36- ..	8000	12.41	7007	716	6231	6221	10.22	19.56	80.44
12	37-5.0200 W	7500	15.80	6315	1117	5198	4960	17.69	38.51	61.49
13	39- ..	9500	14.59	8114	1248	6866	6526	15.38	34.52	65.48
14	40- ..	9500	16.20	7961	1177	6784	6436	14.78	29.84	70.16
15	41- ..	8000	14.40	6848	1384	5460	5226	20.27	43.90	56.10
16	42- ..	7000	17.84	5751	1162	4589	4408	20.21	43.97	56.03
17	43-4.0700 W	9000	18.68	7318	1117	6201	6203	15.26	27.44	72.56
18	44- ..	9000	19.32	7261	955	6306	6219	13.15	24.03	75.97
19	45- ..	9000	18.33	7350	1072	6278	6298	14.58	41.91	58.09
20	46- ..	9000	18.79	7309	936	6373	6259	12.81	23.01	76.99
21	47-6.0402 W	8000	10.72	7142	919	6223	6271	12.86	31.67	68.33
22	48- ..	7500	10.72	6696	636	6060	5999	9.50	20.28	79.72
23	49- ..	7000	11.32	6208	763	5445	5420	12.29	34.45	65.55
24	50- ..	8000	11.23	7102	952	6150	6211	13.40	29.42	70.58
25	51-5.1610 W	7500	11.43	6643	954	5689	5735	14.36	34.52	65.48
26	52- ..	8000	10.94	7125	912	6213	6237	12.80	27.37	72.63
27	53-6.0402 W	8000	10.21	7183	679	6504	6492	9.45	20.61	79.39
28	93-5.1610 W	7500	8.79	6841	757	6084	6074	11.07	14.92	85.08
29	94- ..	7000	8.06	6436	732	5704	5691	11.37	21.45	78.55
30	95- ..	7500	8.44	6867	853	6014	6045	12.42	21.70	78.30
31	96-7.1610 —	7500	7.14	6965	874	6091	6177	12.50	17.82	82.18
32	97- ..	6500	7.14	6036	684	5352	5196	11.33	17.87	82.13

TABLE 29 COAL AND ASH (*Concluded*)

No.	Laboratory File No.	Total Coal and Ash							Analyses of Ash and Refuse	
		Weight of Coal as Fired	Percentage of Moisture in Coal	Total Weight of Dry Coal Fired	Total Ash and Refuse	Total Dry Coal Minus Ash and Refuse	Total Combustible Consumed	Percent of Ash and Refuse Referred to Dry Coal	Carbon	Earthy Matter
1	2	3	4	5	6	7	8	9	10	11
	Code Item	25	26	27	28	30.1	30	31	44	45
		Lb.	%	Lb.	Lb.	Lb.	Lb.	%	%	%
33	98-7.1610-	8000	6.79	7457	879	6578	6548	11.79	16.38	83.62
34	99- "	8000	7.61	7391	949	6442	6480	12.84	16.15	83.85
35	100- "	7500	7.73	6916	835	6081	6172	12.07	16.18	83.82
36	101- "	10000	7.34	9266	1065	8201	8057	11.49	17.44	82.56
37	102-5.1006 W	5500	8.58	5028	488	4540	4517	9.70	13.81	86.19
38	104- "	7000	10.12	6292	675	5617	5578	10.73	15.11	84.89
39	107- "	7000	9.40	6342	667	5675	5669	10.52	14.88	85.12
40	109- "	7000	8.99	6371	717	5654	5684	11.25	14.40	85.60
41	110- "	8500	9.38	7703	848	6855	6782	11.01	13.61	86.39
42	112- "	6000	8.90	5466	692	4774	4849	12.66	14.47	85.53
43	113- "	8500	9.74	7672	845	6827	6821	11.01	14.95	85.05
44	114- "	7000	9.25	6353	718	5635	5539	11.30	14.90	85.10
45	115-6.0200 W	6000	13.94	5164	810	4354	4087	15.69	46.18	53.82
46	116- "	5053	13.97	4347	506	3841	3602	11.64	33.74	66.26
47	117- "	6300	21.49	4946	496	4450	4242	10.03	16.59	83.41
48	118- "	7500	18.52	6111	709	5402	5101	11.60	28.31	71.69
49	119- "	5500	17.34	4546	627	3919	3745	13.79	32.48	67.52
50	120- "	7500	19.27	6055	834	5221	4952	13.77	33.60	66.40
51	121- "	7500	19.63	6028	751	5277	4976	12.46	27.78	72.22
52	122- "	8500	19.49	6843	807	6036	5724	11.79	25.30	74.70
53	124-4.0300 W	10000	21.61	7839	1266	6573	6144	16.15	33.80	66.20
54	125- "	8500	21.72	6654	1021	5633	5207	15.34	32.84	67.16
55	126- "	7627	21.35	5999	864	5135	4748	14.40	33.77	66.23
56	127- "	9404	21.25	7406	1156	6250	5819	15.61	34.98	65.02
57	128-4.0703 W	9000	17.24	7448	759	6689	6539	10.19	25.75	74.25
58	129- "	7777	22.62	6017	534	5483	5375	8.88	15.65	84.35
59	130- "	6000	17.95	4923	726	4197	4354	14.75	18.81	81.19
60	131- "	8000	19.83	6414	629	5785	5688	9.81	17.87	82.13
61	132- "	9201	17.68	7574	733	6841	6709	9.68	19.69	80.31
62	133- "	10500	16.48	8770	845	7925	7828	9.64	18.84	81.16
63	134- "	9600	19.29	7748	763	6985	6912	9.85	19.20	80.80
64	135- "	4600	19.49	3703	414	3289	3300	11.17	14.59	85.41

TABLE 30 STEAM AND WATER BACK

No.	Laboratory File No.	Barometric Pressure	Steam				Water Back				
			Average Gage Pressure	Absolute Pressure	Quality		Total Weight of Water Used	Temperature of Inflow	Temperature of Outflow	Per cent of Total Heat Lost to Water Back	Water Equivalent Correction Factor
					Percentage of Moisture	Factor for Correction for Quality					
1	2	3	4	5	6	7	8	9	10	11	12
	Code Item		11	11.1	54	56	a	b	c	d	e
		Lb.	Lb.	Lb.	%		Lb.	°F.	°F.	%	
1	21—4.0703 W	14.60	151.0	165.6	1.05	.9923	41186	55.0	82.7	1.02	1.0165
2	23—	14.59	151.0	165.6	1.20	.9912	30916	57.0	94.0	1.41	1.0218
3	24—	14.64	152.0	166.6	2.16	.9842	47405	57.0	92.0	1.81	1.0291
4	25—	14.42	152.0	166.4	1.23	.9911	46244	56.0	85.0	1.20	1.0191
5	26—	14.34	152.0	166.3	1.18	.9914	44462	57.0	97.6	1.82	1.0280
6	30—5.0602 W	14.67	152.0	166.7	2.34	.9828	62390	56.0	84.6	2.04	1.0316
7	31—	14.51	151.3	165.8	2.10	.9846	46780	56.0	92.9	1.90	1.0291
8	32—	14.32	151.4	165.7	2.91	.9787	38228	56.0	89.8	2.14	1.0334
9	34—	14.29	150.5	164.8	1.88	.9856	35960	56.0	97.9	1.82	1.0298
10	35—	14.40	150.0	164.4	1.70	.9876	43892	57.0	91.2	1.66	1.0270
11	36—	14.50	150.0	164.5	1.59	.9884	37570	56.0	103.7	1.98	1.0317
12	37—5.0200 W	14.50	150.0	164.5	2.25	.9832	29500	57.0	98.2	1.71	1.0327
	38—	14.43	150.6	164.4	1.70	.9876	38498	57.0	99.8	1.69	
13	39—	14.40	150.0	164.4	2.00	.9854	43060	57.0	97.4	1.86	1.0354
14	40—	14.38	150.0	164.4	1.87	.9863	39332	57.0	96.3	1.67	1.0314
15	41—	14.53	150.0	164.5	1.75	.9872	23471	55.0	99.5	1.39	1.0260
16	42—	14.65	150.0	164.7	2.15	.9843	26314	56.0	101.3	1.88	1.0349
17	43—4.0700 W	14.60	150.0	164.6	1.52	.9889	41543	56.0	105.8	2.34	1.0372
18	44—	14.36	150.0	164.4	1.53	.9888	48059	56.0	106.7	2.73	1.0420
19	45—	14.45	150.1	164.6	1.60	.9883	56481	56.0	96.2	2.52	1.0391
20	46—	14.53	150.0	164.5	1.71	.9875	40416	55.0	113.0	2.61	1.0406
21	47—6.0402 W	14.60	150.0	164.6	1.60	.9883	52811	57.0	112.0	3.19	1.0471
22	48—	14.48	150.0	164.5	1.95	.9857	65935	56.0	93.8	2.84	1.0433
23	49—	14.55	150.0	164.6	1.80	.9868	45114	57.0	119.4	3.58	1.0521
24	50—	14.40	150.0	164.4	0.74	.9946	65277	56.5	97.2	2.96	1.0431
25	51—5.1610 W	14.43	150.0	164.4	0.80	.9942	56076	56.8	102.4	3.04	1.0467
26	52—	14.39	150.0	164.4	0.75	.9945	69329	56.4	92.4	2.76	1.0423
27	53—6.0402 W	14.48	147.0	161.5	0.67	.9951	63780	54.7	93.8	2.65	1.0410
28	93—5.1610 W	14.39	149.9	164.3	1.00	.9927	73131	56.1	81.2	2.08	1.0323
29	94—	14.38	152.8	167.2	1.00	.9927	150302	56.3	69.9	2.48	1.0389
30	95—	14.27	150.0	164.3	1.00	.9927	53404	57.3	94.5	2.27	1.0355
31	96—7.1610—	14.37	150.4	164.8	0.57	.9959	61215	55.8	85.6	2.02	1.0316
32	97—	14.67	152.3	167.0	0.55	.9959	50718	56.1	91.7	2.19	1.0334

TABLE 30 STEAM AND WATER BACK (Concluded)

No.	Laboratory File No.	Barometric Pressure	Steam				Water Back				
			Average Gage Pressure	Absolute Pressure	Quality		Total Weight of Water Used	Temperature of Inflow	Temperature of Outflow	Per cent of Total Heat Lost to Water Back	Water Equivalent Correction Factor
					Percentage of Moisture	Factor for Correction for Quality					
1	2	3	4	5	6	7	8	9	10	11	12
	Code Item		11	11.1	54	56	a	b	c	d	e
		Lb.	Lb.	Lb.	%		Lb.	°F.	°F.	%	
33	98-7.1610-	14.40	150.3	164.7	0.57	.9959	57843	56.4	88.5	1.96	1.0306
34	99- "	14.33	148.2	162.5	0.57	.9959	61228	56.8	83.5	1.73	1.0269
35	100- "	14.44	148.2	162.6	0.57	.9959	54740	56.7	83.0	1.62	1.0258
36	101- "	14.31	146.7	161.0	0.57	.9959	58320	56.5	87.8	1.59	1.0255
37	102-5.1006 W	14.31	147.8	162.1	0.57	.9959	52030	56.9	81.4	1.96	1.0282
38	104- "	14.26	146.7	161.0	0.57	.9959	61168	56.6	86.2	2.24	1.0324
39	107- "	14.29	147.5	161.8	0.57	.9959	77517	57.2	77.9	1.96	1.0290
40	109- "	14.28	148.1	162.4	0.45	.9967	62528	56.8	81.0	1.84	1.0279
41	110- "	14.36	148.5	162.9	0.45	.9967	78897	56.0	78.2	1.78	1.0264
42	112- "	14.10	148.5	162.7	0.75	.9945	75948	57.6	80.1	2.44	1.0360
43	113- "	14.64	148.7	163.3	0.57	.9959	67233	58.0	83.2	1.76	1.0264
44	114- "	14.24	148.1	162.3	0.57	.9959	34393	57.0	86.3	1.28	1.0199
45	115-6.0200 W	14.32	147.1	161.4	0.57	.9959	44895	57.1	79.5	1.74	1.0337
46	116- "	14.23	145.1	158.3	0.57	.9959	40410	57.0	76.4	1.56	1.0304
47	117- "	14.26	145.5	159.8	0.57	.9959	43105	57.9	77.1	1.37	1.0251
48	118- "	14.43	145.8	160.2	0.57	.9959	57240	57.7	79.3	1.70	1.0290
49	119- "	14.44	146.3	160.7	0.57	.9959	62017	56.9	70.8	1.62	1.0298
50	120- "	14.29	147.3	161.6	0.57	.9959	56761	57.0	82.6	2.08	1.0356
51	121- "	14.26	146.3	160.6	0.57	.9959	65280	57.5	75.5	1.67	1.0285
52	122- "	14.25	148.6	162.8	0.57	.9959	72134	57.6	77.0	1.73	1.0293
53	124-4.0300 W	14.38	149.0	163.4	0.57	.9959	72612	56.1	72.2	1.36	1.0233
54	125- "	14.36	148.5	162.9	0.57	.9959	63312	57.0	76.6	1.71	1.0289
55	126- "	14.31	149.2	163.5	0.57	.9959	64500	56.7	71.1	1.40	1.0238
56	127- "	14.27	149.5	163.8	0.57	.9959	62100	57.0	73.7	1.28	1.0215
57	128-4.0703 W	14.22	148.6	162.8	0.57	.9959	94657	56.9	75.4	1.90	1.0272
58	129- "	14.11	149.2	163.3	0.57	.9959	73984	56.7	76.2	1.89	1.0277
59	130- "	14.21	149.1	163.3	0.57	.9959	71182	56.9	79.7	2.62	1.0381
60	131- "	14.14	149.4	163.5	0.57	.9959	85371	57.0	77.4	2.16	1.0308
61	132- "	14.28	149.4	163.7	0.57	.9959	86456	57.0	79.3	2.09	1.0296
62	133- "	14.31	148.3	162.6	0.57	.9959	97785	57.3	76.8	1.76	1.0254
63	134- "	14.17	148.3	162.5	0.57	.9959	69250	57.0	82.1	1.78	1.0257
64	135- "	14.28	147.3	161.6	0.57	.9959	51450	57.7	90.4	3.58	1.0516

TABLE 31 WATER LOG DATA

No.	Laboratory File No.	Feed Water Weighed			Feed Water Corrections							
		Number of Tanks Weighed	Weight per Tank	Total Water Weighed	Water Gage		Feed Tank		Steam Pressure		Miscellaneous Corrections	Total Correction
					Reading at Start	Reading at Close	Level at Start	Level at Close	Start, Gage	Close, Gage		
1	2	3	4	5	6	7	8	9	10	11	12	13
			Lb.	Lb.	In.	In.	In.	In.	Lb.	Lb.	Lb.	Lb.
1	21—4.0703 W	75	801	60075	4.25	4.00	14.70	17.40	153	150		— 351
2	23— ..	55	803	44165	5.60	1.20	25.20	25.00	150	151		+1058
3	24— ..	61	804	49044	3.70	4.50	20.50	20.00	150	151		+ 184
4	25— ..	77	803	61831	4.25	4.80	27.50	34.00	153	150		—1092
5	26— ..	69	803	55407	4.00	3.10	31.75	28.70	151	147	406a	+ 223
6	30—5.0602 W	60	806	48360	5.00	2.50	29.00	28.00	153	153		+ 726
7	31— ..	62	806	49972	5.50	4.75	35.00	26.00	154	151		+1468
8	32— ..	42	806	33852	4.25	7.50	30.25	22.75	154	154		— 49
9	34— ..	54	808	43632	6.00	4.25	24.50	25.25	150	149		+ 292
10	35— ..	60	806	48360	5.25	6.00	22.75	24.75	149	150	300b	— 159
11	36— ..	60	805	48800	3.75	3.25	26.25	22.75	153	148		+ 591
12	37—5.0200 W	40	806	32240	4.75	4.50	25.50	24.50	148	147		+ 196
13	39— ..	53	806	42718	4.50	4.75	23.75	21.50	152	148		+ 241
14	40— ..	52	806	41912	4.50	4.00	26.75	22.25	149	149		+ 772
15	41— ..	44	806	35464	3.50	5.25	28.25	30.25	149	148		— 706
16	42— ..	37	806	29822	5.25	5.75	23.25	26.00	152	150		— 240
17	43—4.0700 W	60	805	48300	3.75	4.50	24.00	22.75	147	147		+ 7
18	44— ..	62	806	49972	4.50	5.25	23.25	20.50	150	160		+ 225
19	45— ..	61	806	49166	5.00	5.00	29.50	20.75	152	151		+1266
20	46— ..	61	806	49166	5.75	6.00	26.50	19.25	151	150	146c	+ 883
21	47—6.0402 W	66	805	53130	4.50	4.50	25.00	22.75	148	151	214c	+ 200
22	48— ..	63	805	50715	4.50	6.00	26.00	27.50	147	149	301c	— 774
23	49— ..	59	805	47495	4.75	5.50	26.25	27.00	146	145	510c	— 665
24	50— ..	67	805	53935	4.80	6.50	27.00	27.30	152	149	494c	— 823
25	51—5.1610 W	59	805	47495	4.00	3.50	22.25	22.80	150	151	530c	— 344
26	52— ..	63	806	50778	4.50	4.25	22.25	20.75	150	152	480c	— 61
27	53—6.0402 W	66	805	53130	4.25	4.50	25.25	25.50	149	151	781c	— 884
28	93—5.1610 W	61	807	49227	6.00	6.00	24.00	26.00	149	153		— 380
29	94— ..	55	807	44385	7.00	5.00	29.00	26.00	148	150		+ 917
30	95— ..	59	807	47613	4.00	3.50	28.00	25.00	152	150		+ 540
31	96—7.1610—	60	807	48420	7.00	5.75	29.00	23.80	150	151		+1054
32	97— ..	53	807	42771	4.00	5.00	27.50	29.75	147	155		— 515

a. Leakage from Pump. b. Valve in weighing tank accidentally opened.

c. Leakage through Blow-off Valve.

TABLE 31 WATER LOG DATA (Concluded)

No.	Laboratory File No.	Feed Water Weighed			Feed Water Corrections							
		Number of Tanks Weighed	Weight Per Tank	Total Water Weighed	WaterGage		Level at Start		Steam Pressure		Miscellaneous Corrections	Total Correction
					Reading at Start	Reading at Close	Level at Start	Level at Close	Start, Gage	Close, Gage		
1	2	3	4	5	6	7	8	9	10	11	12	13
			Lb.	Lb.	In.	In.	In.	In.	Lb.	Lb.	Lb.	Lb.
33	98-7.1610-	64	807	51648	6.00	6.00	29.00	25.80	150	148	.....	+ 454
34	99- " "	65	807	52455	3.00	4.80	27.00	26.00	150	147	.....	- 291
35	100- " "	60	807	48420	3.25	5.50	29.00	28.50	145	153	.....	- 397
36	101- " "	77	807	62139	3.50	2.50	27.00	28.00	149	146	.....	+ 70
37	102-5.1006 W	48	807	38736	5.00	3.25	25.00	25.50	152	144	.....	+ 289
38	104- " "	58	807	46806	7.00	5.00	31.00	25.75	153	151	.....	+1218
39	107- " "	60	807	48420	3.00	4.00	26.00	29.00	147	139	.....	- 716
40	109- " "	58	807	46806	4.00	7.00	27.00	24.00	154	155	.....	- 256
41	110- " "	70	807	56490	5.50	3.50	28.00	28.00	156	148	.....	+ 410
42	112- " "	50	807	40350	2.25	1.75	28.00	30.00	145	141	.....	- 198
43	113- " "	68	807	54876	6.00	3.50	26.50	27.00	150	142	.....	+ 464
44	114- " "	55	807	44385	5.00	5.75	25.00	29.50	150	148	.....	- 842
45	115-6.0200 W	31	807	25017	5.00	3.50	26.50	24.50	150	148	.....	+ 628
46	116- " "	28	807	22596	5.00	5.50	24.00	27.00	141	152	.....	- 490
47	117- " "	34	807	27438	3.50	2.50	29.50	25.00	150	148	.....	+ 876
48	118- " "	46	807	37122	4.50	5.75	25.50	27.00	144	153	.....	- 457
49	119- " "	30	807	24210	6.75	4.50	28.00	27.00	147	150	.....	+ 688
50	120- " "	44	807	35508	3.50	4.00	27.50	29.50	151	147	.....	- 430
51	121- " "	44	807	35508	4.75	3.50	26.00	28.00	151	148	.....	- 17
52	122- " "	51	807	41157	6.50	4.50	25.00	28.50	145	150	.....	- 14
53	124-4.0300 W	54	807	43578	4.00	3.50	27.00	30.00	141	146	.....	- 291
54	125- " "	46	807	37122	5.00	3.50	25.00	28.00	151	150	.....	- 93
55	126- " "	42	807	33894	5.50	3.75	23.50	28.00	154	146	.....	- 293
56	127- " "	51	807	41157	6.50	4.00	24.50	26.25	155	153	.....	+ 316
57	128-4.0703 W	68	807	54876	4.50	3.00	27.00	25.00	154	150	.....	+ 618
58	129- " "	57	807	45999	4.00	5.00	26.50	26.75	151	147	.....	- 292
59	130- " "	45	807	36316	5.00	4.50	27.17	26.00	148	146	.....	+ 274
60	131- " "	62	807	50034	1.75	6.25	25.00	27.50	149	154	.....	-1384
61	132- " "	68	807	54876	5.00	2.00	26.75	23.00	150	146	.....	+1221
62	133- " "	82	807	66174	2.00	5.00	25.00	24.00	150	148	.....	- 565
63	134- " "	70	807	56490	7.00	3.00	30.75	24.50	151	146	.....	+1808
64	135- " "	34	807	27438	5.50	3.25	27.50	27.00	148	150	.....	+ 609

TABLE 32 TOTAL WATER

No.	Laboratory File No.	Total Water							
		Temperature of Feed Water Entering Boiler	Total Weight of Water Fed to Boiler	Equivalent Water Fed to Boiler from and at 212° F.	Water Actually Evap. Corrected for Quality of Steam	Factor of Evaporation	Equivalent Evaporation from and at 212° F.		
							Performance	Compensated for Water Back	Total Loss of Evap. Charged to Water Back
1	2	3	4	5	6	7	8	9	10
	Code Item	20	57	58	59	60	61	61.1	f
		°F.	Lb.	Lb.	Lb.		Lb.	Lb.	Lb.
1	21—4.0703 W	56.0	59724	72326	59274	1.2110	71781	72365	1184
2	23— ..	55.5	45221	54817	44828	1.2122	54340	55525	1184
3	24— ..	56.0	49228	59630	48450	1.2113	58688	60395	1707
4	25— ..	57.0	60739	73512	60198	1.2103	72858	74249	1391
5	26— ..	57.0	55630	67329	55152	1.2103	66750	68619	1869
6	30—5.0602 W	56.0	49086	59458	48242	1.2113	58436	60283	1847
7	31— ..	56.0	51440	62284	50647	1.2108	61323	63087	1784
8	32— ..	56.0	33803	40946	33083	1.2113	40073	41411	1338
9	34— ..	56.0	43924	53183	43291	1.2108	52417	53979	1562
10	35— ..	58.0	48201	58261	47603	1.2087	57538	59091	1553
11	36— ..	57.0	48891	59143	48324	1.2097	58458	60311	1853
12	37—5.0200 W	57.0	32436	39238	31891	1.2097	38579	39840	1261
13	39— ..	57.5	42059	51950	42332	1.2093	51192	53004	1812
14	40— ..	57.8	42684	51600	42101	1.2089	50896	52494	1598
15	41— ..	56.0	34758	42085	34313	1.2108	41546	42626	1080
16	42— ..	56.0	29582	35812	29118	1.2106	35250	36480	1230
17	43—4.0700 W	56.0	48307	58490	47771	1.2108	57841	59992	2151
18	44— ..	56.0	50197	60779	49635	1.2108	60098	62622	2524
19	45— ..	56.0	50432	61063	49842	1.2108	60349	62708	2559
20	46— ..	55.5	50049	60624	49423	1.2113	59866	62296	2430
21	47—6.0402 W	56.0	53330	64572	52706	1.2108	63816	66822	3006
22	48— ..	56.5	49941	60439	49227	1.2102	59575	62154	2579
23	49— ..	56.5	46830	56669	46212	1.2101	55921	58834	2913
24	50— ..	56.0	53112	64250	52825	1.2097	63902	66656	2754
25	51—5.1610 W	57.0	47151	57015	46878	1.2092	56685	59332	2647
26	52— ..	56.5	50717	61378	50438	1.2102	61040	63622	2582
27	53—6.0402 W	54.8	52246	63296	51990	1.2115	62386	65568	2582
28	93—5.1610 W	56.5	48847	59115	48490	1.2102	58683	60578	1895
29	94— ..	57.1	45302	54820	44971	1.2101	54419	56535	2116
30	95— ..	56.3	48153	58289	47801	1.2105	57863	59917	2054
31	96—7.1610 —	56.1	49474	59893	49271	1.2106	59647	61531	1884
32	97— ..	56.7	42256	51155	42083	1.2106	50945	52646	1701

TABLE 32 TOTAL WATER (Concluded)

No	Laboratory File No.	Total Water							
		Temperature of Feed Water Entering Boiler	Total Weight of Water Fed to Boiler	Equivalent Water Fed to Boiler from and at 212° F.	Water Actually Evap. Corrected for Quality of Steam	Factor of Evaporation	Equivalent Evaporation from and at 212° F.		
							Performance	Compensated for Water Back	Total Loss of Evap. Charged to Water Back
1	2	3	4	5	6	7	8	9	10
	Code Item	20	57	58	59	60	61	61.1	f
		°F.	Lb.	Lb.	Lb.		Lb.	Lb.	Lb.
33	98-7.1610-	56.5	52102	63059	51888	1.2103	62800	64721	1921
34	99- "	56.8	52164	63092	51950	1.2095	62833	64523	1690
35	100- "	56.7	48023	58093	47821	1.2097	57849	59341	1492
36	101- "	56.6	62209	75254	61948	1.2097	74938	76849	1911
37	102-5.1006 W	57.0	39025	47193	38861	1.2093	46995	48320	1325
38	104- "	56.6	48024	58090	47827	1.2096	57851	59725	1874
39	107- "	56.7	47704	57698	47504	1.2095	57456	59122	1666
40	109- "	57.0	46550	56298	46396	1.2094	56111	57676	1565
41	110- "	56.9	56900	68832	56712	1.2097	68605	70416	1811
42	112- "	57.5	40152	48536	39931	1.2088	48269	50006	1737
43	113- "	57.9	55340	66878	55113	1.2085	66604	68362	1758
44	114- "	57.0	43543	52657	43364	1.2093	52440	53483	1043
45	115-6.0200 W	57.0	25845	31010	25540	1.2092	30883	31923	1040
46	116- "	57.0	22106	26724	22015	1.2089	26614	27423	809
47	117- "	57.9	28314	34206	28198	1.2081	34066	34921	855
48	118- "	58.0	36665	44291	36515	1.2080	44110	45389	1279
49	119- "	58.0	24898	30079	24796	1.2081	29956	30848	892
50	120- "	57.6	35078	42395	34934	1.2086	42221	23724	1503
51	121- "	58.0	35491	42877	35345	1.2081	42700	43917	1217
52	122- "	58.0	41143	49717	40974	1.2084	49513	50963	1450
53	124-4.0300 W	56.9	43287	52360	43109	1.2096	52145	53360	1215
54	125- "	57.6	37029	44761	36877	1.2088	44577	45865	1288
55	126- "	57.0	33601	40640	33463	1.2095	40473	41436	963
56	127- "	57.1	41473	50157	41302	1.2094	49951	51024	1073
57	128-4.0703 W	57.3	55494	67092	55266	1.2090	66817	68634	1817
58	129- "	57.0	45707	55283	45520	1.2095	55056	56581	1525
59	130- "	57.0	36589	44254	36439	1.2095	44073	45751	1878
60	131- "	57.0	48850	58842	48451	1.2095	58601	60406	1805
61	132- "	57.0	56097	67855	55867	1.2096	67577	69577	2060
62	133- "	58.0	65609	79275	65340	1.2083	78950	80955	2005
63	134- "	58.0	58298	70441	58059	1.2083	70153	71955	1802
64	135- "	59.0	28047	33856	27932	1.2071	33717	35456	1739

TABLE 33 FUEL AND WATER PER HOUR

No.	Laboratory File No.	Fuel per Hour				Water per Hour				
		Dry Coal Fired	Combustible Consumed	Dry Coal Fired per Sq. Ft. of Grate Surface	Combustible Consumed per Sq. Ft. of Water Heating Surface	Evaporated—Corrected for Quality of Steam	Equivalent Evaporation from and at 212° F.			
							Total	Per Square Foot of Water Heating Surface	Compensated for Water Back	
									Total	Per Sq. Ft. of Water Heating Surface
1	2	3	4	5	6	7	8		10	11
	Code Item	46	47	48	49	62	63	64	63.1	64.1
		Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.
1	21—4.0703 W	1148	964	30.05	0.475	7255	8786	4.33	8931	4.40
2	23—	1070	937	28.05	0.462	7373	8937	4.41	9132	4.51
3	24—	910	784	23.83	0.387	5930	7183	3.54	7392	3.64
4	25—	1127	985	29.50	0.486	7553	9141	4.51	9315	4.60
5	26—	1065	913	27.88	0.450	7228	8748	4.32	8993	4.44
6	30—5.0602 W	878	754	22.98	0.372	6030	7304	3.60	7535	3.71
7	31—	938	798	24.56	0.394	6438	7795	3.85	8022	3.96
8	32—	867	753	22.70	0.371	5961	7221	3.56	7462	3.68
9	34—	899	789	23.52	0.389	5971	7230	3.57	7445	3.67
10	35—	872	769	22.84	0.379	5853	7074	3.49	7265	3.58
11	36—	867	770	22.69	0.380	5980	7234	3.57	7463	3.68
12	37—5.0200 W	982	771	25.69	0.380	4957	5997	2.96	6193	3.05
13	39—	1023	823	26.78	0.406	5336	6453	3.18	6681	3.29
14	40—	1023	827	26.78	0.408	5409	6539	3.22	6744	3.32
15	41—	1201	917	31.45	0.452	6020	7289	3.60	7478	3.69
16	42—	1128	864	29.53	0.426	5710	6912	3.41	7153	3.53
17	43—4.0700 W	898	761	23.51	0.375	5861	7097	3.50	7361	3.63
18	44—	900	771	23.57	0.380	6154	7451	3.68	7764	3.83
19	45—	909	779	23.80	0.384	6166	7466	3.69	7758	3.83
20	46—	925	792	24.22	0.391	6256	7579	3.74	7886	3.89
21	47—6.0402 W	859	754	22.48	0.372	6339	7675	3.79	8036	3.97
22	48—	812	727	21.25	0.359	5967	7221	3.56	7536	3.71
23	49—	756	660	19.78	0.325	5624	6806	3.36	7160	3.53
24	50—	854	747	22.35	0.368	6351	7683	3.79	8014	3.95
25	51—5.1610 W	791	683	20.70	0.337	5581	6748	3.33	7063	3.48
26	52—	878	768	22.98	0.379	6213	7519	3.71	7837	3.86
27	53—6.0402 W	855	773	22.38	0.381	6189	7498	3.70	7805	3.85
28	93—5.1610 W	833	739	21.79	0.365	5901	7142	3.52	7372	3.63
29	94—	823	728	21.55	0.359	5753	6962	3.43	7232	3.56
30	95—	851	749	22.28	0.370	5926	7174	3.54	7428	3.66
31	96—7.1610—	844	738	22.10	0.364	5972	7230	3.57	7458	3.68
32	97—	838	722	21.90	0.356	5845	7076	3.49	7312	3.61

TABLE 33 FUEL AND WATER PER HOUR (Concluded)

No.	Laboratory File No.	Fuel per Hour				Evaporated — Corrected for Quality of Steam	Water per Hour			
		Dry Coal Fired	Combustible Consumed	Dry Coal Fired per Sq. Ft. of Grate Surface	Combustible Consumed per Sq. Ft. of Water Heating Surface		Equivalent Evaporation from and at 212° F.			
							Total	Per Square Foot of Water Heating Surface	Compensated for Water Back	
									Total	Per Sq. Ft. of Water Heating Sur- face
1	2	3	4	5	6	7	8	9	10	11
	Code Item	46	47	48	49	62	63	64	63.1	64.1
		Lb.	Lb.	Lb.	Lb.	Lb	Lb.	Lb.	Lb.	Lb.
33	98—7.1610—	890	781	23.28	0.385	6190	7491	3.70	7720	3.81
34	99—	916	803	23.98	0.396	6194	7789	3.84	7998	3.94
35	100—	1017	894	26.62	0.441	7032	8507	4.20	8726	4.31
36	101—	1144	995	29.90	0.491	7648	9251	4.57	9487	4.68
37	102—5.1006 W	831	747	21.75	0.368	6424	7768	3.83	7987	3.94
38	104—	769	682	20.13	0.336	5844	7070	3.49	7299	3.60
39	107—	783	700	20.49	0.345	5865	7093	3.50	7298	3.60
40	109—	815	727	21.34	0.359	5935	7178	3.54	7378	3.64
41	110—	1020	898	26.70	0.443	7510	9084	4.48	9324	4.60
42	112—	696	608	18.23	0.300	5086	6149	3.03	6370	3.14
43	113—	1051	934	27.51	0.461	7550	9124	4.50	9365	4.62
44	114—	1319	1150	34.54	0.568	9002	10886	5.37	11102	5.47
45	115—6.0200 W	644	510	16.86	0.251	3186	3852	1.90	3982	1.96
46	116—	725	600	18.97	0.296	3670	4436	2.19	4571	2.25
47	117—	740	635	19.37	0.313	4219	5097	2.51	5225	2.57
48	118—	769	642	20.12	0.316	4593	5549	2.74	5710	2.82
49	119—	616	507	16.12	0.250	3358	4057	2.00	4177	2.06
50	120—	741	606	19.41	0.299	4277	5170	2.55	5354	2.64
51	121—	754	622	19.73	0.307	4418	5338	2.63	5490	2.70
52	122—	813	680	21.28	0.335	4864	5883	2.90	6055	2.98
53	124—4.0300 W	996	781	26.08	0.385	5479	6628	3.27	6782	3.34
54	125—	820	642	21.46	0.316	4543	5492	2.71	5651	2.79
55	126—	1000	791	26.17	0.390	5577	6745	3.32	6905	3.40
56	127—	1055	829	27.62	0.409	5886	7119	3.51	7272	3.58
57	128—4.0703 W	901	791	23.58	0.390	6685	8082	3.98	8302	4.09
58	129—	885	790	23.16	0.390	6694	8096	3.99	8320	4.10
59	130—	679	601	17.77	0.296	5026	6079	3.00	6311	3.11
60	131—	787	698	20.60	0.344	5945	7190	3.54	7411	3.65
61	132—	867	768	22.70	0.379	6397	7738	3.82	7967	3.93
62	133—	1103	985	28.87	0.486	8219	9931	4.90	10183	5.02
63	134—	1052	938	27.55	0.463	7881	9523	4.70	9768	4.82
64	135—	529	471	13.85	0.233	3990	4817	2.38	5065	2.50

TABLE 34 HORSE POWER AND ECONOMIC RESULTS

No.	Laboratory File No.	Horse Power		Economic Results							
		Developed	Percentage of Builders Rating Developed	Apparent Evaporation per pound of Coal as Fired	Performance			Compensated for Water Back			
					Equivalent Evaporation from and at 212° F.	Apparent Evaporation per Pound of Coal as Fired	Equivalent Evaporation from and at 212° F.	Per Pound of Coal as Fired	Per Pound of Dry Coal	Per Pound of Combustible	
1	2	3	4	5	6	7	8	9	10	11	12
	Code Item	65	67	68	69	70	71	68.1	69.1	70.1	71.1
		H. P.	%	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.
1	21—4.0703 W	254.7	121.3	5.19	6.24	7.65	9.11	5.28	6.34	7.78	9.26
2	23—	259.0	123.3	5.65	6.79	8.35	9.54	5.77	6.94	8.53	9.75
3	24—	208.2	99.1	5.47	6.52	7.89	9.16	5.63	6.71	8.12	9.43
4	25—	265.0	126.2	5.47	6.56	8.11	9.28	5.57	6.69	8.26	9.46
5	26—	253.6	120.8	5.56	6.68	8.21	9.58	5.72	6.87	8.44	9.85
6	30—5.0602 W	211.7	100.8	6.14	7.30	8.32	9.69	6.33	7.53	8.58	10.00
7	31—	225.9	107.6	6.05	7.21	8.31	9.77	6.23	7.42	8.55	10.05
8	32—	209.3	99.7	6.15	7.29	8.32	9.59	6.36	7.53	8.60	9.91
9	34—	209.6	99.8	5.86	6.99	8.05	9.16	6.03	7.20	8.30	9.43
10	35—	205.0	97.6	6.03	7.19	8.11	9.20	6.19	7.38	8.33	9.45
11	36—	202.7	99.9	6.11	7.31	8.34	9.40	6.30	7.54	8.60	9.70
12	37—5.0200 W	173.8	82.8	4.32	5.14	6.11	7.78	4.46	5.31	6.31	8.03
13	39—	187.0	89.0	4.52	5.39	6.31	7.84	4.68	5.62	6.53	8.12
14	40—	189.5	90.2	4.49	5.36	6.39	7.91	4.63	5.53	6.59	8.16
15	41—	211.3	100.6	4.34	5.19	6.07	7.95	4.45	5.32	6.23	8.16
16	42—	200.3	95.4	4.22	5.04	6.13	8.00	4.37	5.22	6.34	8.28
17	43—4.0700 W	205.7	98.0	5.37	6.43	7.90	9.32	5.57	6.67	8.17	9.67
18	44—	216.0	102.9	5.58	6.68	8.28	9.66	5.81	6.96	8.63	10.07
19	45—	216.4	103.0	5.60	6.71	8.21	9.58	5.82	6.97	8.53	9.95
20	46—	219.7	104.6	5.56	6.65	8.20	9.56	5.79	6.92	8.53	9.95
21	47—6.0402 W	222.5	106.0	6.67	7.98	8.94	10.18	6.98	8.36	9.36	10.66
22	48—	202.3	99.7	6.66	7.94	8.90	9.94	6.95	8.28	9.29	10.37
23	49—	197.3	94.0	6.69	7.99	9.01	10.32	7.04	8.41	9.48	10.86
24	50—	222.7	106.0	6.64	7.99	9.00	10.29	6.93	8.33	9.39	10.73
25	51—5.1610 W	195.6	93.1	6.29	7.56	8.53	9.88	6.58	7.91	8.93	10.33
26	52—	217.9	103.8	6.34	7.63	8.57	9.79	6.61	7.95	9.04	10.20
27	53—6.0402 W	217.3	103.5	6.53	7.87	8.77	9.70	6.80	8.19	9.13	10.10
28	93—5.1610 W	207.0	98.6	6.51	7.82	8.58	9.66	6.72	8.07	8.86	9.97
29	94—	201.8	96.1	6.47	7.77	8.46	9.56	6.72	8.07	8.79	9.93
30	95—	207.9	99.0	6.42	7.72	8.43	9.57	6.65	7.99	8.73	9.91
31	96—7.1610—	209.6	99.8	6.60	7.95	8.56	9.66	6.81	8.20	8.83	9.96
32	97—	205.1	97.7	6.50	7.84	8.44	9.80	6.72	8.10	8.72	10.13

TABLE 34 HORSE POWER AND ECONOMIC RESULTS (*Concluded*)

No.	Laboratory File No.	Horse Power		Economic Results							
		Developed	Percentage of Builders Rating Developed	Apparent Evaporation per pound of Coal as Fired	Performance			Compensated for Water Back			
					Equivalent Evaporation from and at 212° F.			Apparent Evaporation per pound of Coal as Fired	Equivalent Evaporation from and at 212° F.		
					Per Pound of Coal as Fired	Per Pound of Dry Coal	Per Pound of Combustible		Per Pound of Coal as Fired	Per Pound of Dry Coal	Per Pound of Combustible
1	2	3	4	5	6	7	8	9	10	11	12
	Code Item	65	67	68	69	70	71	68.1	69.1	70.1	71.1
		H. P.	%	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.	Lb.
33	98-7.1610-	217.1	103.4	6.51	7.85	8.42	9.59	6.71	8.09	8.68	9.88
34	99- "	225.8	107.5	6.52	7.85	8.50	9.70	6.70	8.06	8.73	9.96
35	100- "	246.6	117.4	6.40	7.71	8.36	9.37	6.57	7.91	8.58	9.61
36	101- "	268.1	127.7	6.22	7.49	8.09	9.30	6.38	7.68	8.30	9.54
37	102-5.1006 W	225.2	107.2	7.10	8.55	9.35	10.40	7.30	8.81	9.61	10.69
28	104- "	204.9	97.6	6.86	8.26	9.19	10.37	7.08	8.53	9.40	10.71
39	107- "	205.6	97.9	6.81	8.21	9.06	10.14	7.01	8.45	9.32	10.43
40	109- "	208.1	99.1	6.65	8.02	8.91	9.87	6.85	8.24	9.06	10.15
41	110- "	263.3	125.4	6.69	8.07	8.81	10.12	6.87	8.28	9.15	10.39
42	112- "	178.2	84.9	6.69	8.04	8.83	9.95	6.93	8.33	9.15	10.31
43	113- "	264.5	126.0	6.51	7.84	8.68	9.77	6.68	8.05	8.91	10.03
44	114- "	315.5	150.2	6.22	7.49	8.25	9.47	6.34	7.64	8.41	9.66
45	115-6.0200 W	111.7	53.2	4.27	5.15	5.98	7.56	4.41	5.32	6.18	7.81
46	116- "	128.6	61.2	4.37	5.27	6.12	7.39	4.50	5.43	6.31	7.61
47	117- "	147.7	70.3	4.49	5.41	6.89	8.03	4.60	5.55	7.06	8.23
49	118- "	160.8	76.6	4.89	5.89	7.21	8.65	5.03	6.06	7.42	8.90
50	119- "	117.6	56.0	4.53	5.45	6.59	8.00	4.67	5.61	6.79	8.24
51	120- "	149.9	71.4	4.68	5.63	6.97	8.53	4.85	5.83	7.22	8.83
52	121- "	154.7	73.7	4.73	5.69	7.08	8.58	4.87	5.85	7.28	8.82
53	122- "	170.5	81.2	4.84	5.83	7.23	8.65	4.98	6.00	7.44	8.90
54	124-4.0300 W	192.1	91.5	4.33	5.22	6.65	8.48	4.43	5.34	6.81	8.68
55	125- "	159.2	75.8	4.36	5.25	6.70	8.56	4.49	5.40	6.89	8.81
56	126- "	195.5	93.1	4.41	5.30	6.74	8.52	4.51	5.42	6.90	8.72
57	127- "	206.3	98.2	4.41	5.31	6.74	8.59	4.50	5.42	6.88	8.77
58	128-4.0703 W	234.3	111.6	6.17	7.43	8.97	10.21	6.34	7.63	9.23	10.49
59	129- "	234.7	111.8	5.88	7.08	9.15	10.04	6.04	7.28	9.40	10.32
60	130- "	176.2	83.9	6.10	7.35	8.95	10.12	6.33	7.63	9.29	10.51
61	131- "	208.4	99.2	6.09	7.33	9.14	10.30	6.28	7.56	9.42	10.62
62	132- "	224.3	106.8	6.10	7.35	8.92	10.07	6.28	7.57	9.18	10.37
63	133- "	287.9	137.1	6.25	7.52	9.00	10.09	6.41	7.71	9.23	10.35
64	134- "	276.0	131.4	6.07	7.31	9.05	10.15	6.23	7.50	9.28	10.41
65	135- "	139.6	66.5	6.10	7.33	9.11	10.22	6.41	7.71	9.58	10.75

TABLE 35 EFFICIENCY AND COST OF EVAPORATION

No.	Laboratory File No.	Efficiency				Cost of Coal		
		"Boiler and Furnace"	Over-all	Compensated for Water Back		Per Ton of 3000 Pounds, Delivered	Used to Evaporate 1000 Pounds of Water Under Observed Conditions	Used to Evaporate 1000 Pounds of Water from and at 212° F.
				"Boiler and Furnace"	Over-all			
1	2	3	4	5	6	7	8	9
	Code Item	72	73	72.1	73.1	74	75.1	76.1
		%	%	%	%	Dollars	Dollars	Dollars
1	21--4.0703 W	61.76	57.25	62.78	58.19	1.00	0.095	0.079
2	23-- ..	64.55	62.60	65.96	63.96	1.00	0.087	0.073
3	24-- ..	62.13	59.61	63.94	61.34	1.00	0.090	0.075
4	25-- ..	62.70	60.78	63.90	61.94	1.00	0.090	0.075
5	26-- ..	64.97	62.53	66.79	64.28	1.00	0.088	0.074
6	30--5 0602 W	64.62	62.74	66.66	64.72	1.00	0.080	0.067
7	31-- ..	65.22	61.80	67.12	63.60	1.00	0.081	0.068
8	32-- ..	64.02	62.34	66.16	64.42	1.00	0.080	0.067
9	34-- ..	61.11	60.08	62.93	61.87	1.00	0.084	0.070
10	35-- ..	61.43	60.37	63.09	62.00	1.00	0.082	0.068
11	36-- ..	62.40	60.98	64.38	62.91	1.00	0.080	0.067
12	37--5.0200 W	52.37	48.19	54.08	49.76	1.00	0.114	0.096
13	39-- ..	52.61	49.39	54.47	51.14	1.00	0.108	0.091
14	40-- ..	53.17	50.38	54.84	51.96	1.00	0.109	0.092
15	41-- ..	53.49	47.93	54.88	49.17	1.00	0.114	0.095
16	42-- ..	53.88	48.27	55.76	49.95	1.00	0.116	0.097
17	43--4.0700 W	62.97	60.00	65.31	62.23	1.00	0.091	0.076
18	44-- ..	65.06	62.79	67.79	65.42	1.00	0.087	0.073
19	45-- ..	64.52	62.26	67.04	64.69	1.00	0.087	0.073
20	46-- ..	64.19	62.16	66.80	64.68	1.00	0.088	0.073
21	47--6.0402 W	67.73	64.79	70.92	67.84	1.00	0.073	0.061
22	48-- ..	65.62	64.20	68.46	66.98	1.00	0.073	0.061
23	49-- ..	68.66	65.49	72.24	68.90	1.00	0.072	0.060
24	50-- ..	68.69	65.73	71.65	68.56	1.00	0.073	0.061
25	51--5.1610 W	65.12	61.60	68.16	64.47	1.00	0.077	0.064
26	52-- ..	65.21	62.70	67.97	65.35	1.00	0.077	0.064
27	53--6.0402 W	64.60	63.25	67.25	65.84	1.00	0.074	0.062
28	93--5.1610 W	64.30	63.15	66.38	65.19	1.00	0.075	0.063
29	94-- ..	63.80	62.10	66.28	64.52	1.00	0.075	0.063
30	95-- ..	63.87	61.97	66.14	64.18	1.00	0.076	0.063
31	96--7.1610 W	63.88	62.42	65.90	64.00	1.00	0.074	0.062
32	97-- ..	65.47	64.01	67.82	66.35	....	0.075	0.062

TABLE 35 EFFICIENCY AND COST OF EVAPORATION (Concluded)

No.	Laboratory File No.	Efficiency				Cost of Coal		
		"Boiler and Furnace"	Over-all	Compensated for Water Back		Per Ton of 2000 Pounds, Delivered	Used to Evaporate 1000 Pounds of Water Under Observed Conditions	Used to Evaporate 1000 Pounds of Water from and at 212° F.
				"Boiler and Furnace"	Over-all			
1	2	3	4	5	6	7	8	9
	Code Item	72	73	72.1	73.1	74	75.1	76.1
		¢	¢	¢	¢	Dollars	Dollars	Dollars
33	98-7.1610 —	64.01	62.64	65.97	64.56	1.00	0.075	0.062
34	99— " "	64.40	62.89	66.13	64.58	1.00	0.075	0.063
35	100— " "	62.86	61.54	64.48	63.12	1.00	0.077	0.064
36	101— " "	62.22	60.82	63.81	62.35	1.00	0.079	0.066
37	102-5.1006 W	69.62	68.62	71.58	70.55	1.00	0.069	0.057
38	104— " "	69.13	67.90	71.37	70.10	1.00	0.071	0.059
39	107— " "	67.68	66.50	69.64	68.42	1.00	0.072	0.059
40	109— " "	65.85	64.69	67.69	66.49	1.00	0.074	0.061
41	110— " "	67.47	66.33	69.25	68.08	1.00	0.073	0.061
42	112— " "	67.69	65.30	70.13	67.69	1.00	0.073	0.061
43	113— " "	66.71	65.46	68.47	67.19	1.00	0.075	0.063
44	114— " "	64.23	62.99	65.51	64.24	1.00	0.079	0.066
45	115-6.0200 W	51.62	47.27	53.36	48.86	1.00	0.115	0.095
46	116— " "	51.27	48.94	52.83	50.44	1.00	0.113	0.093
47	117— " "	54.49	53.46	55.86	54.80	1.00	0.110	0.091
48	118— " "	58.71	56.46	60.41	58.10	1.00	0.101	0.084
49	119— " "	54.30	51.49	55.92	53.92	1.00	0.109	0.090
50	120— " "	58.48	55.32	60.56	57.29	1.00	0.105	0.087
51	121— " "	58.63	56.25	60.30	57.86	1.00	0.104	0.086
52	122— " "	58.97	56.93	60.70	58.60	1.00	0.101	0.084
53	124-4.0300 W	58.37	54.61	59.73	55.88	1.00	0.114	0.095
54	125— " "	59.27	55.69	60.98	57.30	1.00	0.113	0.094
55	126— " "	58.75	55.37	60.15	56.68	1.00	0.112	0.093
56	127— " "	59.45	55.56	60.73	56.76	1.00	0.112	0.093
57	128-4.0703 W	69.98	68.00	71.88	69.85	1.00	0.080	0.066
58	129— " "	68.24	68.54	70.13	70.40	1.00	0.083	0.070
59	130— " "	68.81	66.69	71.43	69.23	1.00	0.080	0.064
60	131— " "	70.20	68.86	72.36	70.98	1.00	0.080	0.067
61	132— " "	68.68	67.25	70.71	69.24	1.00	0.080	0.067
62	133— " "	69.38	67.98	71.14	69.68	1.00	0.079	0.065
63	134— " "	69.36	67.82	71.14	69.66	1.00	0.081	0.067
64	135— " "	69.37	68.13	72.95	71.65	1.00	0.079	0.066

TABLE 36 AIR AND FLUE GASES

No.	Laboratory File No.	Air				Flue Gases					
		Average Draft Pressure in. Water		Average Temps.		Average Temperature of Escaping Flue Gases	Analysis of Dry Gases				Average Smoke Ringelmann Chart Number
		Between Damper and Boiler	In Furnace	External Air	Boiler Room		Carbon Dioxide	Oxygen	Carbon Monoxide	Nitrogen	
1	2	3	4	5	6	7	8	9	10	11	12
	Code Item	12	13	15	16	21	84	85	86	88	77
				° F	° F	° F	℄	℄	℄	℄	
1	21—4.0703 W	.....	0.195	20.7	51.6	622	10.36	.....	.....	.....	1.50
2	23— ..	.....	0.157	37.0	63.0	678	8.77	.....	.....	.....	0.00
3	24— ..	.....	0.116	37.0	61.0	611	10.26	.....	.....	.....	0.00
4	25— ..	.....	0.213	.....	.....	708	8.86	.....	.....	.....	0.00
5	26— ..	.....	0.115	47.0	68.0	675	7.82	.....	.....	.....	0.00
6	30—5.0602 W	0.254	0.102	33.0	61.0	639	7.04	.....	.....	.....	0.00
7	31— ..	0.746	0.104	29.8	59.2	638	10.10	.....	.....	.....	0.00
8	32— ..	0.324	0.050	31.0	61.0	650	9.54	.....	.....	.....	0.00
9	34— ..	0.650	0.134	32.0	69.0	645	9.47	.....	.....	.....	0.00
10	35— ..	0.715	0.162	34.0	61.0	612	6.22	.....	.....	.....	0.08
11	36— ..	0.680	0.150	39.5	62.3	653	8.05	.....	.....	.....	0.08
12	37—5.0200 W	0.880	0.270	38.0	60.7	641	7.10	.....	.....	.....	0.00
13	39— ..	1.330	0.380	40.8	59.6	634	6.40	.....	.....	.....	0.00
14	40— ..	1.440	0.430	39.0	62.1	626	5.84	.....	.....	.....	0.00
15	41— ..	1.450	0.290	27.8	57.9	638	7.02	.....	.....	.....	0.00
16	42— ..	1.420	0.270	.....	55.2	620	5.95	.....	.....	.....	0.00
17	43—4.0700 W	0.450	0.130	22.2	51.0	586	10.50	.....	.....	.....	0.00
18	44— ..	0.510	0.130	35.6	59.0	587	10.60	.....	.....	.....	0.00
19	45— ..	0.460	0.106	18.6	66.3	589	11.20	.....	.....	.....	0.00
20	46— ..	0.650	0.145	14.3	44.0	617	9.94	.....	.....	.....	0.00
21	47—6.0402 W	0.420	0.127	28.0	54.9	599	12.40	.....	.....	.....	0.00
22	48— ..	0.500	0.138	33.1	59.5	606	11.01	.....	.....	.....	0.00
23	49— ..	0.350	0.105	31.2	58.2	583	11.79	.....	.....	.....	0.00
24	50— ..	0.340	0.085	35.0	60.1	612	12.08	.....	.....	.....	0.00
25	51—5.1610 W	0.400	0.122	39.2	64.3	615	10.30	.....	.....	.....	0.00
26	52— ..	0.540	0.122	36.0	71.1	647	10.00	.....	.....	.....	0.00
27	53—6.0402 W	0.540	0.122	21.0	51.6	648	9.60	.....	.....	.....	0.00
28	93—5.1610 W	0.399	0.145	53.6	72.7	610	8.88	10.22	0	80.90	0.00
29	94— ..	0.375	0.124	60.7	72.9	608	8.88	10.25	0	80.87	0.00
30	95— ..	0.321	0.103	55.0	74.5	609	9.38	9.66	0	80.96	0.00
31	96—7.1610—	0.321	0.093	42.0	70.3	606	9.32	9.52	0	81.16	0.00
32	97— ..	0.311	0.124	53.4	70.7	600	9.00	9.89	0	81.11	0.00

TABLE 36 AIR AND FLUE GASES (Concluded)

No	Laboratory File No.	Air				Flue Gases					
		Average Draft Pressure in. Water		Average Temps.		Average Temperature of Escaping Flue Gases	Analysis of Dry Gases				Average Smoke Ringelmann Chart Number
		Between Damper and Boiler	In Furnace	External Air	Boiler Room		Carbon Dioxide	Oxygen	Carbon Monoxide	Nitrogen	
1	2	3	4	5	6	7	8	9	10	11	12
	Code Item	12	13	15	16	21	84	85	86	88	77
				° F	° F	° F	%	%	%	%	
33	98—7.1610—	0.354	0.143	62.1	71.5	611	9.40	9.43	0	81.17	0.00
34	99—	0.371	0.116	53.9	73.7	627	9.47	9.40	0	81.13	0.00
35	100—	0.508	0.157	50.7	72.3	655	9.52	9.28	0	81.20	0.00
36	101—	0.720	0.188	56.9	75.2	683	9.02	9.85	0	81.13	0.00
37	102—5.1006 W	0.266	0.097	65.2	74.9	617	10.56	8.00	0	81.44	0.00
38	104—	0.228	0.088	62.7	72.6	611	11.09	7.38	0	81.53	0.00
39	107—	0.250	0.113	76.3	80.3	599	10.79	7.55	0.01	81.65	0.00
40	109—	0.305	0.144	66.2	77.7	607	10.56	7.99	0.01	81.44	0.00
41	110—	0.404	0.146	54.7	74.1	670	11.48	7.34	0.01	81.17	0.00
42	112—	0.184	0.091	80.6	84.3	565	11.27	7.62	0	81.11	0.00
43	113—	0.500	0.174	73.4	82.9	676	11.12	7.78	0	81.10	0.11
44	114—	0.864	0.230	46.8	61.9	748	10.27	8.89	0	80.84	0.21
45	115—6.0200 W	0.560	0.165	54.8	70.3	562	4.62	15.28	0	80.10	0.00
46	116—	0.818	0.313	69.0	75.5	568	4.88	15.03	0	80.09	0.02
47	117—	0.893	0.414	75.4	80.8	581	5.53	14.24	0	80.23	0.00
48	118—	0.830	0.363	60.4	72.6	595	5.98	13.78	0	80.24	0.00
49	119—	0.624	0.303	58.3	67.9	556	5.11	14.71	0	80.18	0.00
50	120—	0.681	0.305	73.7	82.2	574	6.04	13.64	0	80.32	0.00
51	121—	0.862	0.346	82.0	86.9	576	5.87	13.83	0	80.30	0.02
52	122—	0.831	0.364	73.4	81.2	607	6.20	13.41	0	80.39	0.00
53	124—4.0300 W	0.845	0.339	54.2	73.1	622	6.56	12.97	0	80.47	0.00
54	125—	0.667	0.298	64.4	71.0	581	6.16	13.44	0	80.40	0.00
55	126—	0.891	0.367	67.3	74.9	610	6.58	12.93	0	80.49	0.00
56	127—	0.891	0.381	73.0	80.9	624	6.90	12.34	0	80.76	0.00
57	128—4.0703 W	0.303	0.132	57.6	72.2	618	11.08	7.52	0.01	81.39	0.16
58	129—	0.348	0.118	55.0	70.8	633	11.03	7.71	0	81.26	1.20
59	130—	0.150	0.096	67.4	73.3	533	12.50	6.13	0.01	81.36	0.10
60	131—	0.241	0.111	68.4	76.7	574	11.26	7.58	0	81.16	0.20
61	132—	0.325	0.137	69.5	79.0	604	10.98	7.78	0.01	81.23	0.15
62	133—	0.561	0.174	73.1	79.0	667	10.93	7.94	0	81.13	0.18
63	134—	0.495	0.161	66.1	75.6	665	11.18	7.61	0	81.21	0.23
64	135—	0.067	0.058	66.5	76.1	489	12.55	5.94	0.01	81.50	1.00

TABLE 37 PROXIMATE ANALYSES OF COAL

No.	Laboratory File No.	Proximate Analyses								
		Coal as Fired				Pure coal		Italicized Figures are Calculated from Analyses of Composite Samples Indicated	Referred to Combustible	
		Fixed Carbon	Volatile Matter	Moisture	Ash	Fixed Carbon	Volatile Matter		Moisture	Ash
1	2	3	4	5	6	7	8	9	10	11
	Code Item	32	33	34	35	32.1	33.1		34.1	35.1
		%	%	%	%	%	%	Chem. Lab.No. ^a	%	%
1	21—4.0703 W	41.48	32.46	18.38	7.68	56.10	43.90	Comp. No. 253	24.86	10.39
2	23—	41.21	32.24	18.63	7.92	56.10	43.90		25.36	10.79
3	24—	41.37	32.83	17.35	8.45	55.75	44.25		23.38	11.39
4	25—	40.90	32.01	19.11	7.98	56.10	43.90	Comp. No. 253	26.21	10.95
5	26—	40.60	31.73	18.71	8.91	56.10	43.90		25.85	12.31
6	30—5.0602 W	47.85	29.76	12.24	10.15	61.65	38.35	Comp. No. 272	15.77	13.08
7	31—	47.59	30.38	13.15	8.88	61.04	38.96		16.87	11.39
8	32—	48.05	29.91	12.49	9.55	61.65	38.35	Comp. No. 273	16.02	12.25
9	34—	47.87	29.78	13.13	9.22	61.65	38.35		16.91	11.87
10	35—	49.04	30.52	11.30	9.14	61.65	38.35		14.20	21.49
11	36—	49.28	30.28	12.41	8.08	61.92	38.08		15.61	10.16
12	37—5.0200 W	43.08	28.78	15.80	12.33	59.95	40.05	Comp. No. 303	21.98	17.16
13	39—	43.93	29.33	14.59	12.18	59.95	40.05		19.92	16.63
14	40—	42.82	28.61	16.20	12.36	59.95	40.05		22.68	17.30
15	41—	43.73	29.21	14.40	12.66	59.95	40.05		19.74	17.36
16	42—	42.13	28.14	17.84	11.89	59.95	40.05		25.39	16.92
17	43—4.0402 W	39.41	32.98	18.68	8.93	54.43	45.57	Comp. No. 302	25.80	12.34
18	44—	39.00	32.65	19.32	9.03	54.43	45.57		26.96	12.60
19	45—	40.51	34.16	18.33	6.70	54.43	45.57		24.45	8.94
20	46—	39.91	32.02	18.79	9.28	55.48	44.52		26.12	12.90
21	47—6.0402 W	49.52	32.45	10.72	7.31	60.41	39.59	Comp. No. 304	13.08	8.92
22	48—	50.12	31.58	10.72	7.58	61.35	38.65		13.12	9.28
23	49—	49.04	32.14	11.32	7.50	60.41	39.59	Comp. No. 304	13.94	9.24
24	50—	49.01	32.12	11.23	7.64	60.41	39.59		13.84	9.42
25	51—5.1610 W	54.05	26.80	11.42	7.72	66.85	33.15		14.14	9.55
26	52—	49.78	31.31	10.94	7.97	61.40	38.60	Comp. No. 502	13.49	9.83
27	53—6.0402 W	50.08	32.62	10.21	6.89	60.41	39.59	Comp. No. 304	12.32	8.31
28	93—5.1610 W	50.65	31.64	8.79	8.72	61.40	38.60	Comp. No. 502	10.66	10.57
29	93—	51.29	32.25	8.06	8.40	61.40	38.60		9.65	10.06
30	95—	51.01	32.07	8.44	8.48	61.40	38.60		10.16	10.21
31	93—7.1610	51.01	33.43	7.14	8.42	60.41	39.59		8.46	9.97
32	97—	50.06	31.76	7.14	11.04	61.18	38.82	Comp. No. 519	8.73	13.49

(a) For Analysis of the Composite Samples, see page 5.

TABLE 37 PROXIMATE ANALYSES OF COAL (*Concluded*)

No.	Laboratory File No.	Proximate Analyses								
		Coal as Fired				Pure Coal		Italicized Figures are Calculated from Analyses of Composite Samples Indicated	Referred to Combustible	
		Fixed Carbon	Volatile Matter	Moisture	Ash	Fixed Carbon	Volatile Matter		Moisture	Ash
1	2	3	4	5	6	7	8	9	10	11
	Code Item	32	33	34	35	32.1	33.1		34.1	35.1
		%	%	%	%	%	%	Chem. Lab.No.	%	%
33	98-7.1610—	51.18	32.47	6.79	9.56	61.18	38.82	Comp. No. 519	8.12	11.43
34	99—	50.73	32.10	7.61	6.47	61.18	38.82	"	9.18	11.42
35	100—	51.45	32.64	7.78	8.13	61.18	38.82	"	9.25	9.67
36	101—	50.44	31.99	7.34	10.23	61.18	38.82	"	8.90	12.41
37	102-5.1006 W	52.02	31.31	8.58	8.09	62.43	37.57	.....	10.30	9.71
38	104—	50.68	30.46	10.12	8.74	62.46	37.54	Comp. No. 571	12.47	10.77
39	107—	51.46	30.33	9.40	8.21	62.46	37.54	"	11.41	9.96
40	109—	51.64	31.03	8.99	8.34	62.46	37.54	"	10.87	10.09
41	110—	50.66	30.46	9.38	9.50	62.46	37.54	"	11.56	11.71
42	112—	51.53	30.97	8.90	8.60	62.46	37.54	"	10.79	10.42
43	113—	51.04	30.69	9.74	8.53	62.46	37.54	"	11.92	10.44
44	114—	50.37	30.28	9.25	10.10	62.46	37.54	"	11.47	12.52
45	115-6.0200 W	46.56	27.79	13.94	11.71	62.62	37.38	.....	18.75	15.75
46	116—	46.60	28.07	13.97	11.36	62.41	37.59	Comp. No. 578	18.71	15.21
47	117—	42.84	25.80	21.49	9.87	62.41	37.59	"	31.31	14.38
48	118—	44.12	26.58	18.52	10.78	62.41	37.59	"	26.20	15.25
49	119—	44.81	26.99	17.34	10.86	62.41	37.59	"	34.15	15.13
50	120—	43.53	26.22	19.27	10.98	62.41	37.59	"	27.63	15.74
51	121—	43.14	25.99	19.63	11.24	62.41	37.59	"	28.40	16.26
52	122—	43.52	26.22	19.49	10.77	62.41	37.59	"	27.95	15.44
53	124-4.0300 W	36.65	29.07	21.61	12.67	55.77	44.23	.....	32.88	19.28
54	125—	36.47	28.73	21.72	13.08	55.94	44.06	Comp. No. 600	31.31	20.06
55	126—	36.96	29.11	21.35	12.58	55.94	44.06	"	32.31	19.04
56	127—	37.02	29.15	21.25	12.58	55.94	44.06	"	32.11	19.01
57	128-4.0703 W	42.94	31.89	17.24	7.93	57.39	42.61	.....	23.04	10.60
58	129—	39.56	30.64	22.63	7.17	56.35	43.65	Comp. No. 608	33.24	10.21
59	130—	42.17	32.67	17.95	7.21	56.35	43.65	"	23.98	9.63
60	131—	41.60	30.89	19.83	7.68	56.39	42.61	.....	27.36	10.59
61	132—	41.97	32.51	17.68	7.84	56.35	43.65	Comp. No. 608	23.74	10.53
62	133—	42.82	33.24	16.48	7.46	56.30	43.70	"	21.67	9.81
63	134—	41.43	32.09	19.29	7.19	56.35	43.65	Comp. No. 608	26.24	9.78
64	135—	41.62	31.43	19.49	7.46	56.98	43.02	.....	26.68	10.21

TABLE 38 ULTIMATE ANALYSES OF COAL

No.	Laboratory File No.	Ultimate Analyses of Moisture Free Coal						
		Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur	Ash	Italicized Figures Are Calculated from Analyses of Composite Samples Indicated
1	2	3	4	5	6	7	8	9
	Code Item	37	38	33	40	41	42	
		%	%	%	%	%	%	Chem. Lab. No.
1	21—4.0703 W	72.92	4.70	9.65	1.22	2.10	9.41	Comp. No. 253
2	23—	72.48	4.68	9.59	1.22	2.29	9.74	
3	24—	72.00	4.95	9.37	1.22	2.24	10.22	
4	25—	72.51	4.68	9.59	1.25	2.10	9.87	Comp. No. 253
5	26—	71.51	4.61	9.47	1.24	2.21	10.96	
6	30—5.0602 W	72.51	4.61	8.47	1.35	1.50	11.56	Comp. No. 273
7	31—	73.54	4.64	8.67	1.36	1.56	10.23	
8	32—	73.09	4.65	8.54	1.37	1.44	10.91	Comp. No. 273
9	34—	73.40	4.67	8.56	1.38	1.38	10.61	
10	35—	73.48	4.68	8.58	1.47	1.49	10.30	
11	36—	74.37	4.44	9.34	1.35	1.28	9.22	
12	57—5.0200 W	69.46	4.32	8.76	1.37	1.44	14.65	Comp. No. 303
13	39—	69.81	4.34	8.81	1.39	1.39	14.26	Comp. No. 303
14	40—	69.46	4.32	8.75	1.36	1.36	14.75	
15	41—	69.23	4.31	8.73	1.53	1.41	14.79	
16	42—	69.51	4.33	8.77	1.55	1.37	14.47	
17	43—4.0700 W	70.29	4.60	10.50	1.50	2.07	11.04	Comp. No. 302
18	44—	70.10	4.60	10.48	1.48	2.15	11.19	
19	45—	72.60	4.76	10.85	1.47	2.12	8.20	
20	46—	70.80	4.59	9.76	1.19	2.23	11.43	
21	47—6.0402 W	74.72	4.77	9.08	1.68	1.56	8.19	Comp. No. 304
22	48—	74.77	4.70	9.29	1.33	1.42	1.42	
23	49—	74.46	4.76	9.04	1.68	1.60	1.60	Comp. No. 304
24	50—	74.39	4.76	9.03	1.68	1.54	1.54	
25	51—5.1610 W	74.39	4.53	9.40	1.35	1.61	8.72	
26	52—	73.49	4.99	9.45	1.71	1.41	8.95	Comp. No. 502
27	53—6.0402 W	75.22	4.81	9.14	1.69	1.47	7.67	Comp. No. 304
28	93—5.1610 W	73.55	4.99	9.44	1.29	1.37	9.56	Comp. No. 502
29	94—	73.66	5.01	9.47	1.31	1.41	9.14	
30	95—	73.59	5.00	9.47	1.30	1.38	9.26	
31	96—7.1610 W	73.65	5.34	8.83	1.24	1.87	9.67	
32	97—	71.02	4.58	9.13	2.19	1.19	11.89	Comp. No. 519

TABLE 38 ULTIMATE ANALYSES OF COAL

No.	Laboratory File No.	Ultimate Analyses of Moisture Free Coal						
		Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur	Ash	Italicized Figures Are Calculated from Analyses of Composite Samples Indicated
1	2	3	4	5	6	7	8	9
	Code Item	37	38	39	40	41	42	
		%	%	%	%	%	%	Chem.-Lab. No.
33	98-7.1610 —	71.88	4.62	9.23	1.21	2.79	10.27	Comp. No. 519
34	99— " "	72.35	4.67	9.31	1.37	2.05	10.25	" "
35	100— " "	73.53	4.74	9.45	1.38	2.09	8.81	" "
36	101— " "	71.18	4.59	9.15	1.33	2.71	11.04	" "
37	102-5.1006 W	74.43	5.04	8.91	1.42	1.36	8.84	.....
38	104— " "	72.97	4.61	9.73	1.45	1.52	9.73	Comp. No. 571
39	107— " "	73.70	4.65	9.83	1.47	1.29	9.06	" "
40	109— " "	72.60	4.64	9.81	1.46	1.33	9.16	" "
41	110— " "	72.44	4.57	9.66	1.40	1.40	10.48	" "
42	112— " "	73.47	4.63	9.79	1.43	1.23	9.45	" "
43	113— " "	73.44	4.63	9.73	1.36	1.33	9.45	" "
44	114— " "	72.06	4.55	9.60	1.34	1.32	11.13	" "
45	115-6.0200 W	70.15	4.48	8.95	1.20	1.61	13.61	Comp. No. 587
46	116— " "	70.27	4.39	9.36	1.08	1.70	13.21	.....
47	117— " "	70.77	4.41	8.41	1.22	1.62	12.57	" "
48	118— " "	70.20	4.38	9.34	1.21	1.64	13.23	" "
49	119— " "	70.31	4.39	9.35	1.21	1.61	13.13	" "
50	120— " "	69.99	4.37	9.30	1.18	1.56	13.60	" "
51	121— " "	69.55	4.33	9.25	1.19	1.69	13.99	" "
52	122— " "	70.12	4.38	9.32	1.21	1.60	13.37	" "
53	124-4.0300 W	66.47	4.47	9.28	1.17	2.45	16.16	.....
54	125— " "	66.89	4.39	8.47	1.09	2.45	16.71	Comp. No. 600
55	126— " "	67.53	4.43	8.55	1.11	2.39	15.99	" "
56	127— " "	67.51	4.44	8.55	1.09	2.43	15.98	" "
57	128-4.0703 W	77.91	4.69	10.44	1.23	2.15	9.58	.....
58	129— " "	72.55	4.82	10.33	1.20	1.84	9.26	Comp. No. 608
59	130— " "	73.00	4.85	10.39	1.25	1.73	8.78	" "
60	131— " "	72.02	5.11	10.25	1.20	1.85	9.57	.....
61	132— " "	72.23	4.80	10.28	1.22	1.95	9.52	Comp. No. 608
62	133— " "	72.83	4.84	10.36	1.21	1.83	8.93	" "
63	134— " "	72.84	4.84	10.37	1.24	1.81	8.90	" "
64	135— " "	72.66	4.77	10.24	1.23	1.83	9.27	.....

TABLE 39 ULTIMATE ANALYSES OF COMBUSTIBLE AND CALORIFIC VALUES

No.	Laboratory File No.	Ultimate Analyses of Pure Coal						Calorific Value by Oxygen Calorimeter	
		Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur	Italicized Figures Are Calculated from Analyses of Composite Samples Indicated	Per Pound of Moisture Free Coal	Per Pound of Combustible
1	2	3	4	5	6	7	8	9	10
	Code Item	37.1	38.1	39.1	40.1	41.1		50	51
		%	%	%	%	%	Chem. Lab. No.	B. t. u.	B. t. u.
1	21—4.0703 W	80.49	5.19	10.65	1.35	2.32	Comp. No. 253	12906	14247
2	23—	80.32	5.18	10.61	1.35	2.54		12883	14273
3	24—	80.20	5.51	10.44	1.36	2.49		12784	14239
4	25—	80.45	5.19	10.64	1.39	2.33	Comp. No. 253	12886	14295
5	26—	80.31	5.18	10.64	1.39	2.48		12680	14241
6	30—5.0602 W	82.00	5.22	9.57	1.52	1.69	Comp. No. 273	12808	14483
7	31—	81.92	5.17	9.66	1.51	1.74		12987	14467
8	32—	82.05	5.22	9.58	1.54	1.61	Comp. No. 273	12889	14468
9	34—	82.11	5.22	9.59	1.54	1.54		12941	14477
10	35—	81.92	5.22	9.56	1.64	1.66		12975	14465
11	36—	81.92	4.89	10.29	1.49	1.41		13208	14549
12	37—5.0200 W	81.38	5.06	10.26	1.61	1.69	Comp. No. 303	12246	14348
13	39—	81.42	5.06	10.28	1.62	1.62	Comp. No. 303	12339	14391
14	40—	81.47	5.07	10.26	1.60	1.60		12249	14368
15	41—	81.24	5.06	10.25	1.80	1.65		12230	14353
16	42—	81.28	5.06	10.25	1.81	1.60		12266	14341
17	43—4.0700 W	79.01	5.17	11.60	1.69	2.33	Comp. No. 302	12717	14295
18	44—	78.93	5.18	11.60	1.67	2.42		12735	14340
19	45—	79.08	5.19	11.62	1.60	2.31		12735	14340
20	46—	79.94	5.18	11.02	1.34	2.52		12740	14384
21	47—6.0402 W	81.38	5.20	9.89	1.83	1.70	Comp. No. 304	13327	14516
22	48—	81.71	5.14	10.15	1.45	1.55		13388	14630
23	49—	81.34	5.20	9.87	1.84	1.75	Comp. No. 304	13288	14516
24	50—	81.39	5.21	9.88	1.84	1.68		13225	14469
25	51—5.1610 W	81.50	4.96	10.30	1.48	1.76		13375	14653
26	52—	80.71	5.48	10.38	1.88	1.55	Comp. No. 502	13201	14499
27	53—6.0402 W	81.47	5.21	9.90	1.83	1.59	Comp. No. 304	13391	14503
28	93—5.1610 W	81.10	5.52	10.44	1.43	1.51	Comp. No. 502	13122	14509
29	94—	81.08	5.51	10.42	1.44	1.55		13149	14472
30	95—	81.10	5.51	10.44	1.43	1.52		13131	14471
31	96—7.1610 —	81.00	5.87	9.71	1.36	2.06		13251	14573
32	97—	80.60	5.20	10.36	1.35	2.49	Comp. No. 519	12737	14456

TABLE 39 ULTIMATE ANALYSES OF COMBUSTIBLE AND CALORIFIC VALUES

No.	Laboratory File No.	Ultimate Analyses of Pure Coal						Calorific Value by Oxygen Calorimeter	
		Carbon	Hydrogen	Oxygen	Nitrogen	Sulphur	Italicized Figures Are Calculated from Analyses of Composite Samples Indicated	Per Pound of Moisture Free Coal	Per Pound of Combustible
1	2	3	4	5	6	7	8	9	10
	Code Item	37.1	38.1	39.1	40.1	41.1		50	51
		%	%	%	%	%	Chem. Lab. No.	B. t. u.	B. t. u.
33	98-7.1610 —	80.10	5.16	10.28	1.35	3.11	Comp. No. 519	12985	14470
34	99 — "	80.62	5.20	10.37	1.53	2.28	"	13057	14548
35	100 — "	80.63	5.21	10.37	1.51	2.29	"	13127	14395
36	101 — "	80.00	5.16	10.29	1.50	3.05	"	12842	14436
37	102-5.1006 W	81.65	5.53	9.77	1.56	1.49	.....	13152	14427
38	104 — "	80.83	5.10	10.77	1.61	1.69	Comp. No. 571	13077	14487
39	107 — "	81.05	5.11	10.80	1.62	1.42	"	13159	14470
40	109 — "	81.02	5.11	10.80	1.60	1.47	"	13151	14477
41	110 — "	80.92	5.11	10.78	1.62	1.57	"	12969	14487
42	112 — "	91.13	5.12	10.81	1.58	1.36	"	13062	14425
43	113 — "	81.10	5.11	10.81	1.51	1.47	"	12808	14145
44	114 — "	81.09	5.11	10.80	1.51	1.48	"	12655	14240
45	115-6.0200 W	81.20	5.19	10.36	1.39	1.86	.....	12220	14145
46	116 — "	80.97	5.06	10.76	1.25	1.96	Comp. No. 587	12081	13920
47	117 — "	80.94	5.05	10.76	1.39	1.86	"	12444	14233
48	118 — "	80.91	5.04	10.77	1.40	1.88	"	12345	14229
49	119 — "	80.94	5.06	10.76	1.39	1.85	"	12361	14229
50	120 — "	81.00	5.06	10.76	1.37	1.81	"	12171	14087
51	121 — "	80.86	5.04	10.76	1.37	1.97	"	12156	14133
52	122 — "	80.94	5.05	10.76	1.39	1.86	"	12272	14166
53	124-4.0300 W	79.29	5.33	11.07	1.39	2.92	.....	11764	14031
54	125 — "	80.30	5.28	10.17	1.31	2.94	Comp. No. 600	11617	13948
55	126 — "	80.39	5.27	10.18	1.32	2.84	"	11766	14005
56	127 — "	80.35	5.28	10.18	1.30	2.89	"	11724	13954
57	128-4.0703 W	79.53	5.19	11.54	1.36	2.38	.....	12740	14990
58	129 — "	79.96	5.31	11.38	1.32	2.03	Comp. No. 608	12893	14210
59	130 — "	80.03	5.32	11.039	1.37	1.89	"	12963	14212
60	131 — "	79.64	5.65	11.34	1.32	2.05	"	12815	14171
61	132 — "	79.83	5.30	11.37	1.35	2.15	Comp. No. 608	12813	14161
62	133 — "	79.97	5.31	11.38	1.33	2.01	"	12791	14045
63	134 — "	79.96	5.31	11.38	1.36	1.99	"	12875	14133
64	135 — "	79.98	5.25	11.39	1.36	2.02	.....	12910	14229

TABLE 40 FURNACE CONDITIONS

No.	Laboratory File No.	Furnace Conditions During Test									
		Fuel at Rear of Grate				Fuel Bed for Four Hour Period		Area of Holes in Fuel Bed			Average Stoker Travel square feet per hour
		Per cent of Time			Average Distance Clear	Number of Times		Average	For 15 Min. Period		
		Banked	Close	Clear		Sliced	Leveled		Maximum	Minimum	
1	2	3	4	5	6	7	8	9	10	11	12
		Per cent			In.	No.	No.	Square inches		Sq. ft.	
1	21—40703 W	23	50	27	6	...	2	0	0	0	65.5
2	23—	0	42	58	4½	1	0	0	0	0	68.8
3	24—	8	48	44	9½	1	0	0	0	0	67.9
4	25—	0	32	68	3	1	0	0	0	0	53.7
5	26—	0	7	93	3½	1	0	0	0	0	101.2
6	30—5.0602 W	0	20	80	4	1	0	0	0	0	75.1
7	31—	8	0	92	2	1	0	0	0	0	82.9
8	32—	0	47	53	3½	1	0	0	0	0	59.0
9	34—	0	48	52	8	1	0	0	0	0	50.9
10	35—	4	48	48	4½	1	0	0	0	0	42.4
11	36—	4	48	48	4½	1	0	0	0	0	49.1
12	37—5.0200 W	10	90	0	0	0	16	210	300	0	72.1
13	39—	5	20	75	7	0	6	100	300	0	53.1
14	40—	0	15	85	6½	0	15	150	400	150	64.0
15	41—	0	5	95	7	0	8	300	600	0	124.0
16	42—	0	5	95	8	0	9	100	400	0	128.4
17	43—4.0700 W	5	25	70	5	1	...	0	0	0	70.4
18	44—	8	3	89	6	1	0	0	0	0	72.4
19	45—	0	0	100	3½	1	0	0	0	0	92.4
20	46—	3	0	97	3	1	0	0	0	0	62.1
21	47—6.0402 W	0	0	100	4	1	30	0	0	0	51.0
22	48—	0	0	100	3	1	20	0	0	0	40.7
23	49—	0	12	88	3	1	20	0	0	0	53.7
24	50—	0	20	80	4	1	5	0	0	0	76.4
25	51—5.1610 W	0	64	36	4	1	8	0	0	0	46.9
26	52—	0	40	60	5	1	8	0	0	0	50.0
27	53—6.0402 W	0	12	88	5½	1	8	0	0	0	50.0
28	93—5.1610 W	0	0	100	3¾	1	8	0	0	0	40.2
29	94—	0	0	100	3½	2	6	3	100	0	46.8
30	95—	0	0	100	4	2	8	0	0	0	58.3
31	96—7.1610 —	0	0	100	3½	4	12	6	200	0	55.0
32	97—	0	0	100	3½	4	10	0	0	0	43.1

TABLE 40 FURNACE CONDITIONS (Concluded)

No.	Laboratory File No.	Furnace Conditions During Test									
		Fuel at Rear of Grate				Fuel Bed for Four Hour Period		Area of Holes in Fuel Bed			Average Stoker Travel square feet per hour
		Per cent of Time			Average Distance Clear	Number of Times		Average	For 15 Min. Period		
		Banked	Close	Clear		Sliced	Leveled		Maximum	Minimum	
1	2	3	4	5	6	7	8	9	10	11	12
		Per cent			In.	No.	No.	Square inches		Sq. ft.	
33	98--7.1610--	0	0	100	3½	5½	11	0	0	0	40.8
34	99--	0	0	100	4	3	7	0	0	0	50.5
35	100--	0	0	100	4¼	1	7	0	0	0	55.3
36	101--	0	6	94	3	2	7	0	0	0	61.4
37	102--5.1006 W	0	0	100	4	2	9	0	0	0	55.4
38	104--	0	0	100	4	3	8	0	0	0	52.8
36	107--	0	0	100	3½	3½	11	0	0	0	42.8
40	109--	0	0	100	3¾	3½	12	0	0	0	38.3
41	110--	0	0	100	4	2	12	0	0	0	55.7
42	112--	0	0	100	3¾	2	11	0	0	0	45.0
43	113--	0	0	100	3½	1	12	0	0	0	56.7
44	114--	0	0	100	3½	2	12	10.5	200	0	68.7
45	115--6.0200 W	0	0	100	5	0	18	22.0	500	0	85.7
46	116--	0	0	100	4½	1	17	0	0	0	55.9
47	117--	0	0	100	4¼	1	18	0	0	0	44.6
48	118--	0	0	100	3¾	2	17	0	140	0	52.2
49	119--	0	0	100	4¼	1½	16	2	50	0	44.4
50	120--	0	0	100	4	1½	15	2	50	0	63.0
51	121--	0	0	100	4¾	1½	17	2	50	0	62.1
52	122--	0	0	100	4	2	22	0	0	0	64.3
53	124--4.0300 W	0	0	100	4	1	16	0	0	0	87.8
54	125--	0	0	100	4¼	1	15	0	0	0	69.6
55	126--	0	0	100	3¾	1½	18	0	0	0	86.6
56	127--	0	0	100	3¾	2	21	0	0	0	89.3
57	128--4.0703 W	0	0	100	4	1	13	0	0	0	69.2
58	129--	0	0	100	4	1½	6	0	0	0	75.2
59	130--	0	0	100	4½	2	8	1.6	50	0	51.7
60	131--	0	0	100	4	1½	10	0	0	0	59.8
61	132--	0	0	100	4	1	10	0	0	0	61.5
62	133--	0	0	100	4¼	1	11	0	0	0	85.3
63	134--	0	0	100	3½	2	12	0	0	0	82.8
64	135--	0	0	100	3½	2	7	0	0	0	38.7

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A STUDY IN HEAT TRANSMISSION

(THE TRANSMISSION OF HEAT TO WATER IN TUBES AS
AFFECTED BY THE VELOCITY OF THE WATER)

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A STUDY IN HEAT TRANSMISSION

I. INTRODUCTION¹

The following experiments, preliminary in nature, were undertaken with two objects in view; (1) to determine the effect of the velocity of the flow of the water on the heat transmitted through the walls of tubes; (2) to determine if the methods of experimentation used were applicable and desirable for a more extensive investigation of the subject, provided this seemed justifiable by the results obtained.

In the flow of heat from a medium, gaseous or liquid, in contact with a metal plate, to a medium in contact with the opposite side of the plate, there are three resistances to be overcome: the two film resistances, that is, the resistance between the liquid and the plate on each side, and the resistance due to the metal of the plate. In the case of liquids in contact with metal plates, it will be found that the first two resistances are considerable as compared with the resistance of the plate itself, and also that these film resistances depend upon the nature of the medium in contact with the plate, and the relative movement or agitation between the plate and the medium. Owing, therefore, to the multiplicity of media and to the state of these media, as found in practice, it was considered advisable to endeavor to determine the rate of flow (or transmission) of heat as a function of the three factors, temperature of tube, temperature of water and velocity of water.

II. DESCRIPTION OF APPARATUS

The apparatus (Fig. 1) consisted of the steam jacket *F* provided with flanges and stuffing boxes at each end. The steam was admitted at *C* and bubbled up through the water in the jacket,

¹Acknowledgment.—Credit is due Mr. A. P. Kratz for assistance in the taking of readings and in making the computations.

which was kept at a constant level, and then passed out the exhaust at *D*. The pressure of the steam in the jacket, and therefore the temperature, was maintained constant by placing a safety valve on the exhaust pipe, and allowing the steam to blow through this valve throughout the tests. The bubbling of the steam through the water prevented the possibility of superheat due to throttling at the valve *C*.

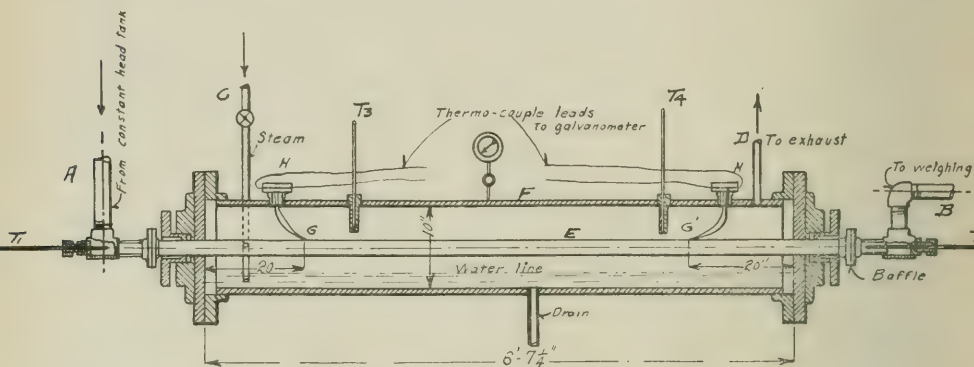


FIG I

TRANSMISSION OF HEAT THROUGH

BOILER TUBES

The tube through which the flow of heat was measured was a 1-in. Shelby cold-drawn steel tube, outside diameter 1.253 in.; inside diameter .985 in., and walls .134 in. thick. This tube was centered through the steam jacket, as shown, and packed around the ends. Each end was threaded, and a flange coupling used to connect the tube on the entering end with the water supply pipe *A*, and on the discharge end with the swinging ell at *B*. Rubber gaskets $\frac{1}{4}$ -in. thick were placed between these couplings; on the discharge end, a sheet metal baffle was inserted. Another baffle was inserted in the pipe *A* about 18 in. above the tee. The object of these baffles was to break up the stream lines before reaching the thermometers T_1 and T_2 . This was done in order that the average temperature of the water might be determined. The couplings were drawn together with insulated bolts. The insulation, together with the gaskets, was used to prevent the conduction of heat back on the tube. The water supply was taken from

a constant head tank, located about 25 ft. above the tube, which permitted a maximum velocity of about 17 ft. per second. The velocity through the tube was regulated to suit the demands by means of a throttle valve placed in the pipe *A*. The steam supply was taken from the laboratory mains.

III. MEASUREMENT OF TEMPERATURES

The temperature of the water, entering and leaving, was taken with mercury thermometers reading directly to tenths; these readings could be estimated to hundredths of degrees C. The thermometers were passed through the stuffing boxes and were in direct contact with the water. The baffles, above mentioned, insured the breaking up of the stream lines, so that very nearly the average temperature of the water was obtained. This was tested by changing the position of the thermometers.

The temperature of the steam was also taken with mercury thermometers T_3 and T_4 , passed through stuffing boxes, so that their bulbs were in direct contact with the steam. Allowance was made for the error due to the pressure of the steam on the bulb. The drawing shows these thermometers placed in thermometer cups; the cups, however, were taken out before the regular experiments were begun and replaced by stuffing boxes.

The temperature of the steam wall of the tube was taken by means of copper-constantan thermocouples and a Siemens and Halske millivoltmeter. The couples were located at G and G' , 20 in. from the face of each flange. The ends of the couples were soldered into small holes, about $\frac{1}{8}$ in. in diameter, and about $\frac{1}{16}$ in. deep, which were drilled in the surface of the tube. The leads were brought out through small glass tubing to the pipe flanges at HH , and then between two rubber gaskets placed between the flanges.

The mean temperature of the tube was taken as the average of the temperatures taken with the two couples, and is given in column 6 of Table 1. All readings were taken in Centigrade units and later changed to Fahrenheit.

TABLE 1

No.	Temperatures in Degrees F.										Water				Conductance		
	Entering Av.	Leaving Av.	Rise	Steam in Jacket	Steam Wall of Tube. Mean	Drop from Steam to Wall of Tube	Drop through Metal of Tube	Water Wall of Tube	Water in Tube. Mean	Drop from Wall of Tube to Water	Weight of Water per Minute	Velocity of Water in ft. per second	B. t. u. per sq. ft. per Minute	Conductance of Film on Steam Side	Conductance of Film on Water Side	Conductance of Tube and Film on Water Side	
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	
1	56.92	66.75	9.83	210.9	181.2	92.4	35.2	146	65.9	80	331.7	16.78	2537	.458	.528	.367	
2	58.32	78.12	19.80	274.4	202.0	72.4	34.7	167	68.2	99	244.4	12.37	2501	.576	.421	.312	
3	58.15	75.45	17.30	273.9	193.2	80.5	36.5	157	66.8	90	294.3	14.89	2631	.544	.487	.347	
4	57.90	80.94	23.04	273.9	203.0	70.9	33.1	170	69.4	100	200.5	10.15	2387	.561	.389	.300	
5	58.03	85.83	27.80	274.1	208.0	66.1	31.0	177	71.9	105	155.7	7.89	2237	.561	.354	.273	
6	58.10	92.88	34.78	274.1	211.0	63.1	28.9	182	75.5	106.5	116.0	5.88	2083	.550	.325	.256	
7	62.87	120.46	57.59	274.1	235.0	39.1	23.8	211	91.7	119	57.6	2.94	1715	.730	.240	.200	
8	63.28	108.50	45.22	274.5	227.0	47.5	24.8	202	86.0	116	35.7	3.80	1786	.698	.256	.211	
9	63.73	145.90	82.17	274.5	239.7	34.8	21.0	219	105.0	114	35.7	1.84	1516	.724	.222	.187	
10	67.55	162.20	94.65	274.4	243	31.4	19.0	224	114.0	110	28.0	1.45	1369	.724	.207	.177	
1	67.54	85.00	17.46	306.6	219.9	86.7	43.6	176	76.3	100	348.4	17.64	3144	.605	.525	.365	
2	67.54	87.19	19.65	306.6	219.0	87.6	43.2	176	74.4	102	306.4	15.50	3112	.591	.508	.357	
3	67.54	93.30	25.76	306.6	230.5	76.1	41.6	189	80.4	109	226.0	11.43	2998	.655	.469	.333	
4	58.73	107.62	48.96	306.8	246.4	60.4	36.7	210	83.2	127	104.7	5.33	2649	.731	.347	.280	
5	58.90	118.05	59.16	307.0	252.3	54.7	34.7	217	88.5	129	81.8	4.17	2501	.761	.322	.234	
6	59.27	129.70	70.43	307.0	255.7	51.3	31.3	224	94.5	129	62.0	3.17	2256	.731	.291	.234	
7	59.52	154.35	94.83	307.4	261.1	46.3	28.8	232	107.0	125	42.5	2.19	2081	.750	.278	.226	
1	57.67	80.50	22.83	330.2	220	110.2	55.2	165	69.0	96.0	338.4	17.13	3955	.606	.684	.440	
2	57.67	83.86	26.21	330.0	220.4	100.6	52.0	177	70.8	106.0	277.4	14.05	3785	.621	.591	.396	
3	58.28	90.92	32.64	330.0	233.1	96.9	47.8	185	74.6	110.0	205.0	10.39	3455	.584	.524	.365	
4	58.17	97.90	39.73	330.2	241.8	88.4	45.1	197	78.07	119.0	158.7	8.06	3260	.614	.437	.331	
5	58.50	120.60	62.10	330.2	257.4	72.8	37.0	220	89.5	130.5	83.3	4.25	2672	.611	.340	.265	
6	58.89	161.50	102.61	330.2	267.1	63.1	32.8	234	110.2	124.0	44.7	2.31	2370	.625	.318	.251	

IV. OBSERVATIONS

The velocity of the flow of the water through the tube was obtained by weighing the total amount discharged over a given period of time. This time was measured with a stop watch. In calculating the volume of water discharged, corrections were made for the different temperatures of this discharge.

Observations were taken over periods of from 3 to 12 minutes, depending upon the velocity of the water. During these periods, six readings of the thermometers were made, so that all of the temperatures given in Table 1 are the average of six readings. At the beginning of a period, an observer swung the end of the discharge pipe *B* over a tank previously balanced on a pair of platform scales, and at the same time snapped the stop watch. The temperatures were then read at equal intervals during the period. At the end of the period, the pipe *B* was swung from over the water tank.

Observations were taken for four different temperatures of the steam in the jacket, 210.9° , 274° , 307° , and 330° F., and for each jacket temperature the water velocity was varied from about .4 to 17 ft. per second. In these experiments, no attempt was made to keep the temperature difference constant between the steam in the jacket and the mean temperature of the water.

V. CALCULATIONS

Referring to Table 1, column 14, the British thermal units per square foot per minute have been computed from the weight of water per minute, column 12; the rise in temperature of the water, column 4; and the area of the tube, computed from the mean diameter.

The mean temperature of the water, column 10, is the average of the items of columns 2 and 3. The curves of Fig. 2 show that within the temperature range of these experiments, this will be the true mean value.

The formula for the flow of heat through a given medium is similar to that for the flow of an electric current, and may be obtained as follows:

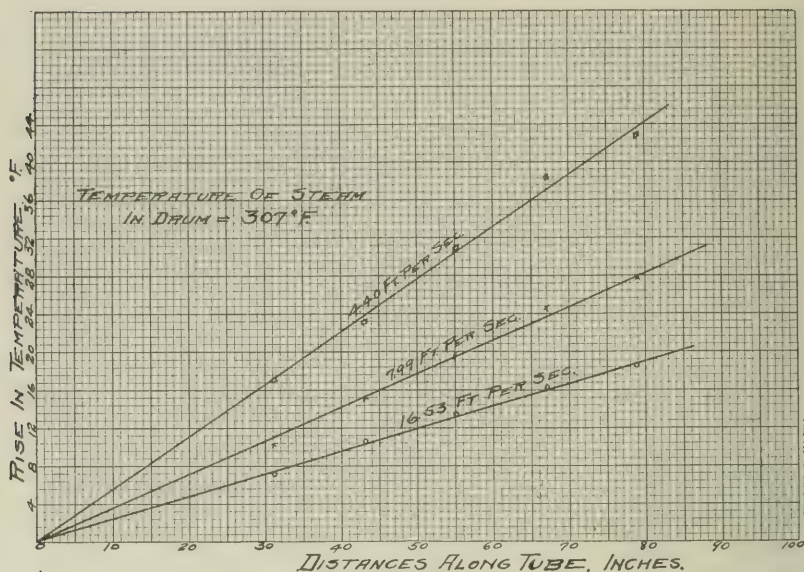


FIG. 2

Let Q = B. t. u. flowing per square foot per second.

$(t-t_1)$ = the temperature drop in degrees F. between two planes cutting the medium parallel to each other, and perpendicular to the direction of flow.

A = area in square feet of a section through which the heat is transmitted.

S = the time in seconds during which the flow takes place.

L = length in inches of the medium or the perpendicular distance between the two planes.

K = the conductivity of the medium, which is equal to the number of B. t. u. transmitted per second, per degree difference in temperature F., per square foot of area per inch of length.

Then
$$Q = \frac{(t-t_1) \times A \times S \times K}{L} \dots \dots \dots (1)$$

The quantity K has been determined experimentally by a number of experimenters, and in c. g. s. units is about .2 for boiler iron. Reducing this to B. t. u., square feet, degrees F., and inches, we obtain the value, .1612 = K = the conductivity of boiler iron. The reciprocal of the conductivity is equal to the specific

resistance =
$$\frac{1.0}{.1612} = 6.2$$

In the present case the thickness of the wall of the tube is .134 in. The resistance of the metal of the tube per square foot, therefore, = $6.2 \times .134 = .831$ and the "conductance" is

$$\frac{1.0}{.831} = 1.204. \quad \text{This value has been assumed to be constant}$$

for the temperatures here used.

It will be well to point out here the distinction between "conductivity" and "conductance", as used in the present article. Conductivity has been used to designate that quantity of heat which will flow through a medium of unit length and of unit area in a unit of time with a temperature drop of one degree, while "conductance" is independent of the length of the medium. The distinction is made necessary on account of the unknown thickness of the steam and water films.

The conductance of the water film, or the B. t. u. transmitted per square foot per second through this film may be determined in the following manner:

Let Q = B. t. u. transmitted per square foot per second.

A = area of the surface of the film in square feet.

S = time in seconds.

K'' = conductance of the water film.

K''_1 = conductivity of the water film.

L'' = thickness of water film, and can not readily be determined.

$(t'' - t''_1)$ = drop in temperature between the inner or water surface of the tube and the water.

$$Q = \frac{K''_1 (t'' - t''_1) \times A \times S}{L''} \dots \dots \dots (2)$$

and

$$K'' = \frac{K''_1}{L''} = \frac{Q}{(t'' - t''_1) A \times S} \dots \dots \dots (3)$$

In order to determine $(t'' - t''_1)$, it will be necessary to determine the temperature of the inner or water surface of the tube. The temperature of the steam surface is given in Table 1, column 6. From formula 1, having Q , which is obtained from Table 1, column 14, and K , given, the temperature drop through the metal of the tube may be computed. This has been done and the results are given in column 8. By subtracting the temperature drop through the metal of the tube from the temperature of the

steam surface of the tube, the temperature of the water surface is obtained. This is given in column 9, and the drop from the water surface to the mean temperature of the water is given in column 11. Having this drop, the conductance of the water film may be computed from the formula.

A consideration of the phenomena occurring on the steam side of the tube is foreign to the purpose of this paper. As, however, the application of the results of experiments along this line have already proved of the greatest practical value in the design of high vacuum apparatus, and as our data are so closely related to this side of the problem, that is, the transmission of heat from the steam to the tube, it will probably not be amiss to devote a small amount of space to this phase of the subject.

On the steam side of the tube, if a condition of equilibrium is assumed to maintain, there will be the condition of saturated steam imparting its heat to a film of water on the surface of the tube, which film may be assumed to be of a constant thickness, and which is constantly being replaced or renewed by the condensation of fresh steam. The agitation of the steam in contact with the water film will, therefore, if it does not agitate this film, have no effect upon the rate of heat transmission or the conductance, at least, in the case of the present experiments; for the maximum velocity of approach of the steam towards the tube, due to the condensation, is about $\frac{1}{3}$ ft. per second. This would lead one to believe that the temperature on the surface of separation of the steam from the water film must be practically the temperature of the saturated steam. If such is the case, the agitation of the steam alone would not affect the conductance, as it would not change the temperature drop through the tube. The solution of the problem of more efficient heat transmission from steam to surface of tube, therefore, lies solely in the removal or agitation of the water film.

If it is then assumed that the temperature of the surface of water film in contact with the steam is at the temperature of the steam, and that the temperature of the surface of the water film in contact with the tube is at the temperature of the tube, the conductance of the water film on the steam side of the tube may be computed from the following:

Let $K' =$ conductance of the film.

$K'_1 =$ conductivity of the film.

L' = thickness of film in inches.

A = area of surface of film in square feet.

S = time in seconds.

Q = B. t. u. transmitted per square foot per second.

$(t' - t'_1)$ = temperature drop between steam in jacket and outer surface of tube, as obtained by thermocouples.

$$Q = \frac{K'_1 (t' - t'_1) A \times S}{L'} \dots \dots \dots (4)$$

therefore

$$K'_1 = \frac{K'_1}{L'_1} = \frac{Q}{(t' - t'_1) \times A \times S} \dots \dots \dots (5)$$

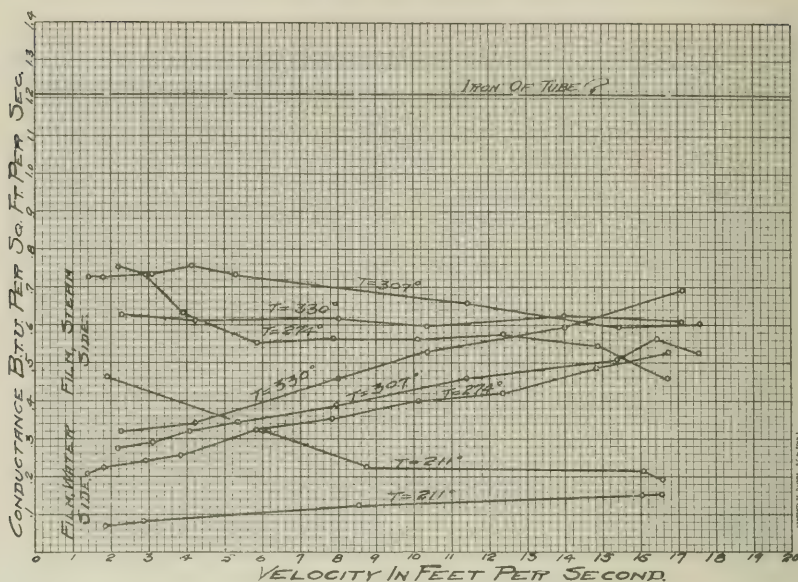
In the above formula A and S may be taken as unity; Q is obtained from Table 1, column 14; the values here given are expressed in B. t. u. per minute and must be reduced to B. t. u. per second before being used in the formula.

$(t' - t'_1)$ is taken from column 7 of the same table.

The value of L' can not be determined.

The conductances of the water films on the steam and water sides of the tube are given in columns 15 and 16, respectively, and these results are shown plotted against the velocity in feet per second of the water in the tube, Fig. 3. The temperatures placed on these curves are the temperatures in the steam jacket during each experiment. The data from which the points on the 211° curve were plotted were taken from the results of some later experiments, and have not been included in the table.

It will be seen from this figure, that the conductance of the film on the water side increases with the velocity of the flow of the water in the tube. This increased conductance at the higher velocities, which means a higher rate of agitation of the water, is due to the increased number of particles of the water coming in contact with the walls of the tube. The word "conductance" used to express the flow of heat from tube to water is somewhat inappropriate in this place, for it seems to suggest that the film remained the same so far as its physical structure was concerned, and that its heat conductivity varied, while as a matter of fact, the increased conductance or the increased flow of heat from the tube to the water at the higher velocities is due to the destruction or rather to the continuous renewal of this film. In the case of water flowing in a tube at velocities lower than the critical ve-



locity, where the stream lines are parallel, we can consider that this stream of water is made up of concentric cylinders of water, the central cylinder of which is moving at the highest velocity, and the velocity of the outer cylinders gradually drops off until the lowest velocity is found in that cylinder which is in direct contact with the walls of the tube. In this case, the heat flow from the walls of the tube takes place principally by conduction, and the effect of convection is very small. The case is analogous to that of heating water in a vessel from the top, such as has been used for the determination of the specific conductivity of water and other liquids. When the critical velocity of the water in the tube is reached, or when baffles are placed so as to disturb the parallelism of the stream lines, the concentric cylinders of water disappear and the stream lines mingle and flow from side to side in zigzag fashion; the film of water adjoining the tube walls is being continually renewed by these zigzag stream lines, and the flow of heat from tube to water is carried on largely by convection.

The conductance of the film on the steam side has been computed and the results are given in column 15 of the table. These conductances have also been plotted against the velocity of flow of the water in the tube and are shown in Fig. 3.

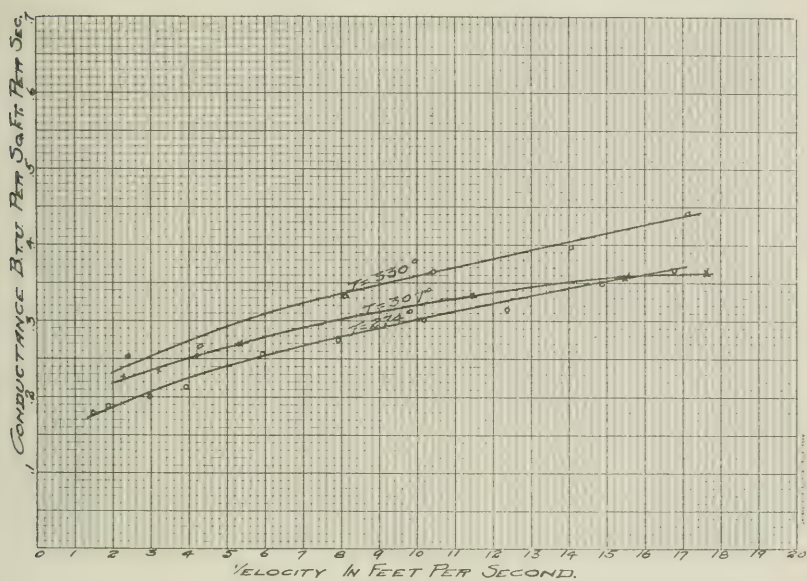


Fig. 4

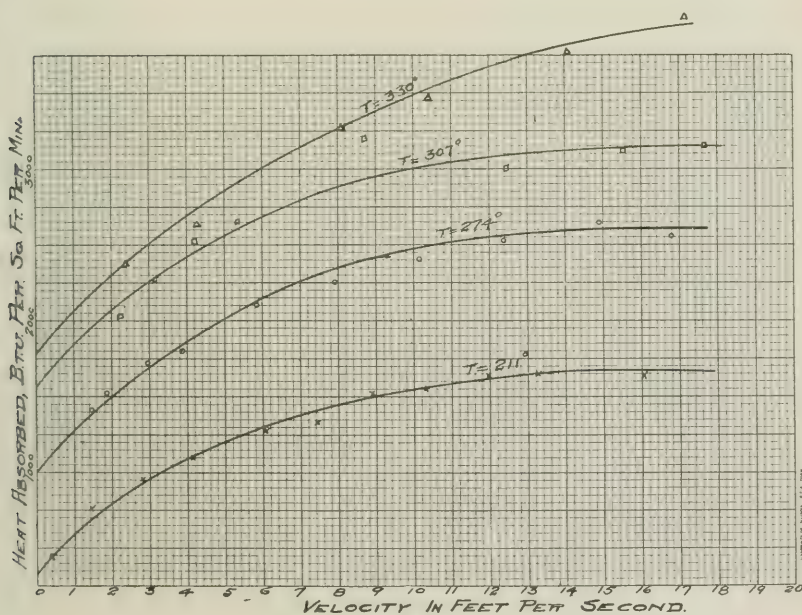


Fig. 5

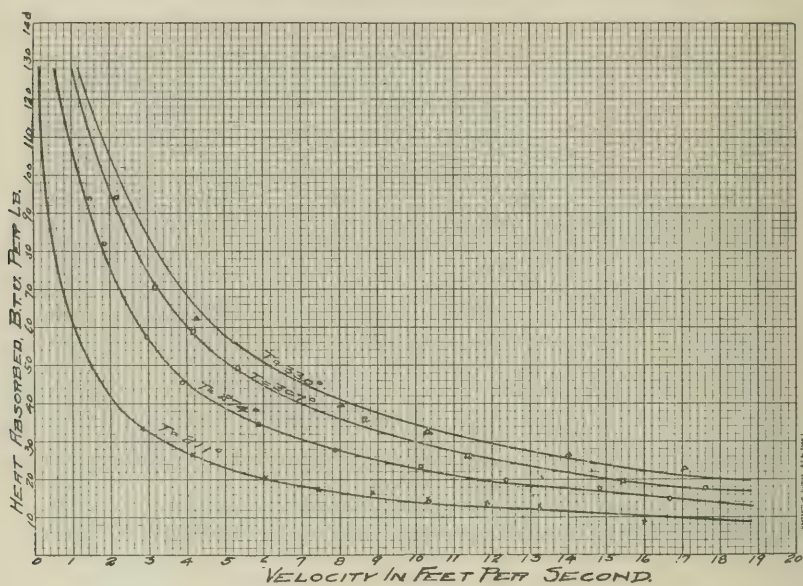


Fig. 6

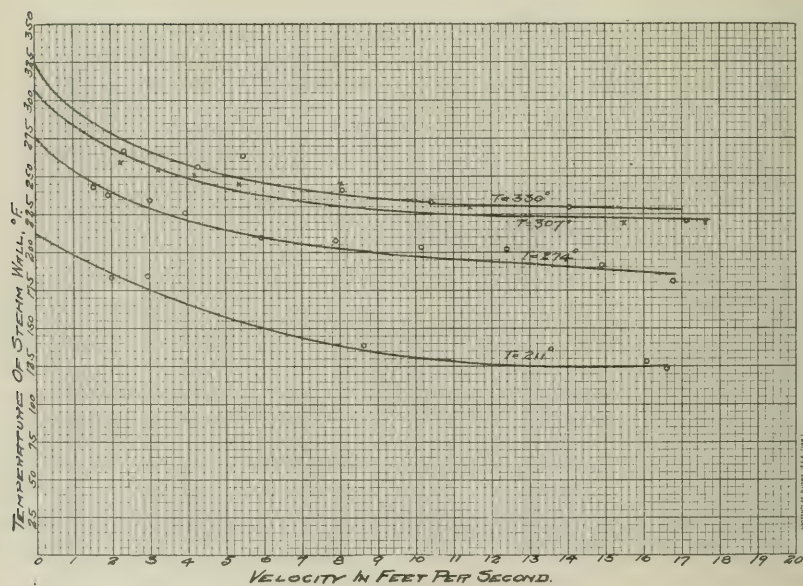


Fig. 7

It will be noted that the conductance of the steam film increases as the velocity of the water in the tube decreases. This is doubtless due to the decrease in temperature difference between the steam and the water as the velocity of the latter is decreased. This results in less condensation on the tube, consequently a thinner layer or water film on the surface of the tube, which makes a higher conductance possible.

The curve taken with a steam temperature of 330° in the jacket is almost a straight line. The other curves also tend to assume a straight line at the higher velocities, which means at the higher temperature differences. It is possible that the former curve would rise suddenly at the smaller velocities.

In Fig. 3 is also shown the straight dashed line indicating the constant conductance of the metal of the tube, which is 1.204.

In column 17 of the table, are given the conductances through tube and film on the water side. These were computed by taking the reciprocal of the sum of the reciprocals of the conductances of the tube and of the film on the water side; the former of which is constant and equal to 1.204, while the latter is obtained from column 16 of the table. The conductances of tube and film are shown in Fig. 4 plotted against the velocity of flow of the water.

The curves of Fig. 5 show the relation between the velocity of the flow of the water in the tube and the total heat transmitted per minute per square foot of mean tube surface. Curves of Fig. 6 show the relation between the velocity of the water and the B. t. u. absorbed per pound. The curves of Fig. 2 were obtained by a set of separate experiments to investigate the rise in temperature of the water along the tube. The temperatures in the tube were taken by means of a thermocouple placed in the end of a long glass tube which was pushed through a perforated cork placed in the end of the water or boiler tube. Beyond the end of the glass tube and ahead of the thermocouple junction, a small baffle was placed so that the mean temperature of the water might be obtained. It will be seen that the rise in temperature is proportional, within the limits of these experiments, to the distance from the entering end of the tube.

In Fig. 7, the temperature of the steam surface of the tube is plotted against velocity of water in feet per second. These curves by their uniformity seem to indicate the reliability of this method of experimentation.

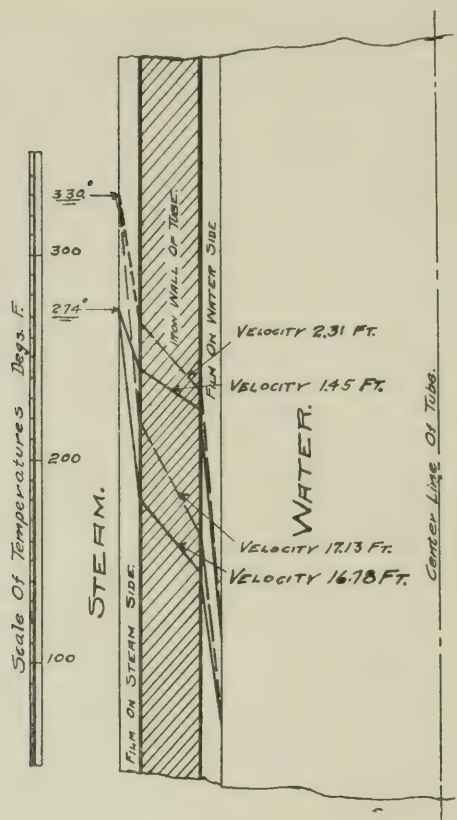


FIG. 8

Fig. 8 is a graphical representation of the temperature gradient through the film on the steam side, the tube and the film on the water side. The values corresponding to the maximum and the minimum velocities, as obtained in the experiment, have been plotted for the steam temperatures of 330° and 274° maintained in the jacket. Fig. 8 illustrates the increased temperature gradient due to the increase of the velocity of flow of the water in the tube. Fig. 8 is interesting in several respects. It illustrates very clearly the effect and importance of the film resistance in all heat transmission problems. It further shows that the film resistance of the metal in the case of tube and plates is much less than the resistance of the films. It may even be used to illustrate why it is possible to lubricate a gas engine with cylinder oil having a flash point of 700° F. while the temperature of the gases in the cylinder may be close to 2500° F.

VI. CONCLUSIONS

The limited nature of these experiments forbids the drawing of any general conclusions other than those already known. The principal interest lies in the development of a method which seems to offer a very desirable means of studying the effect of the variation of the velocity of the flow of gas, steam or water on the rate of flow of heat through tubes, plates, etc.

In order to investigate this subject of the effect of velocity on heat transmission more carefully, means should be provided for maintaining the tube and the water at a constant temperature, while varying the velocity of the latter. In studying the effect on the heat transmission of the velocity of gases over the tube, means should be provided for varying the velocity of the gas, while maintaining a constant temperature of the gas and the tube.

The effect of the formation of steam on the walls of the tube, as it approaches the condition in steam boiler practice, should come in for consideration. It is probable that the effect of rapid agitation of the water in a tube in which steam is forming, especially in large quantities, will be much greater on the heat transmission through the tube to the water, than would be the case in a tube in which no steam was forming, owing of course, to the breaking up and washing off of the steam bubbles from the side of the tube. It might be well to point out here that it is the rate of agitation, and not necessarily the velocity of the water that produces the change in heat transmission. The velocity in feet per second has been used for the reason that it is the only definite quantity available to express this rate of agitation. It may be, to a certain extent, a measure of the rate of agitation, but it is not necessarily so. The rate of agitation may be defined as the number of times per second that each particle of water comes into contact with the tube or with the film on the tube if we consider that the film is indestructible, although it is more likely that the film is in a process of continuous renewal. In the case of the present experiments, it is probable that if elaborate baffles had been placed in the tube, the heat transmission for the same velocity of flow would have been increased. Also, if the stream of water on entering the tube had been given a rotary motion, the heat transmission would have been increased while the velocity through the tube remained constant.

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- *Bulletin No. 2.* Tests of High-Speed Tool Steels on Cast Iron, by L. P. Breckenridge and Henry B. Dirks. 1905.
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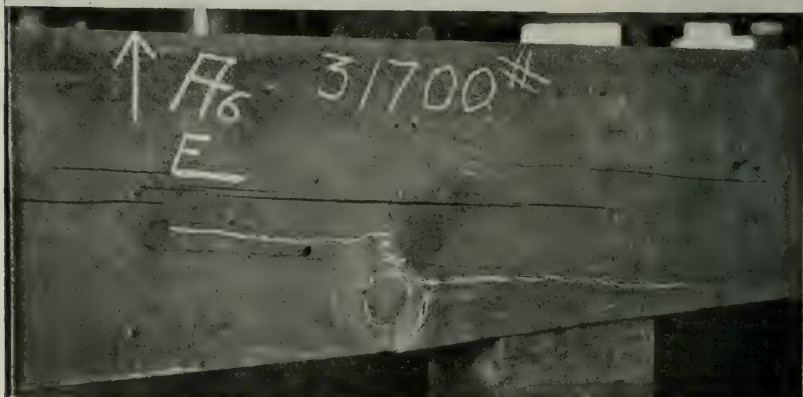
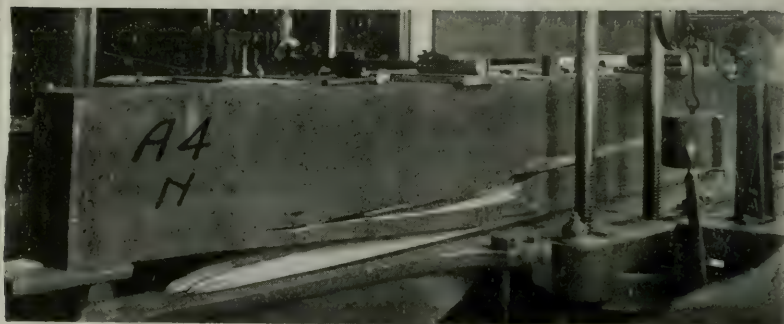
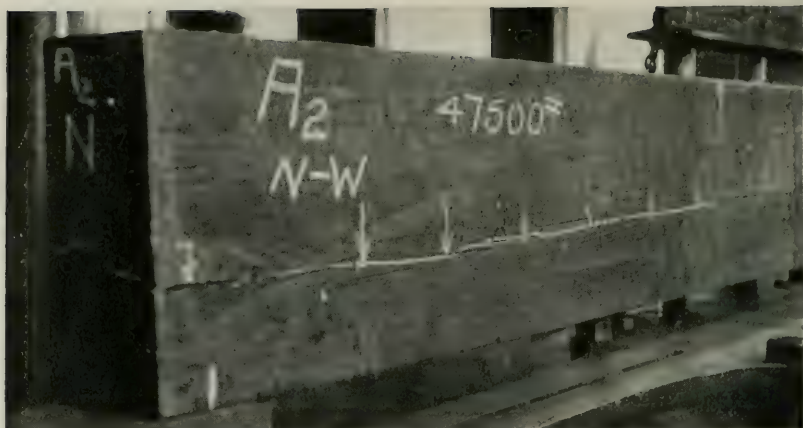


PLATE 1. VIEWS OF BEAMS AFTER FAILURE.

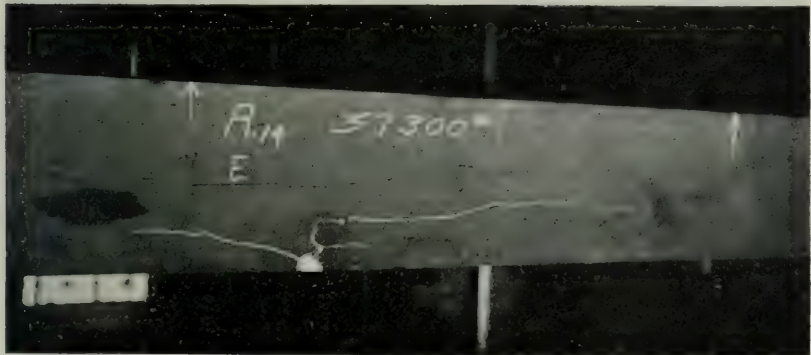
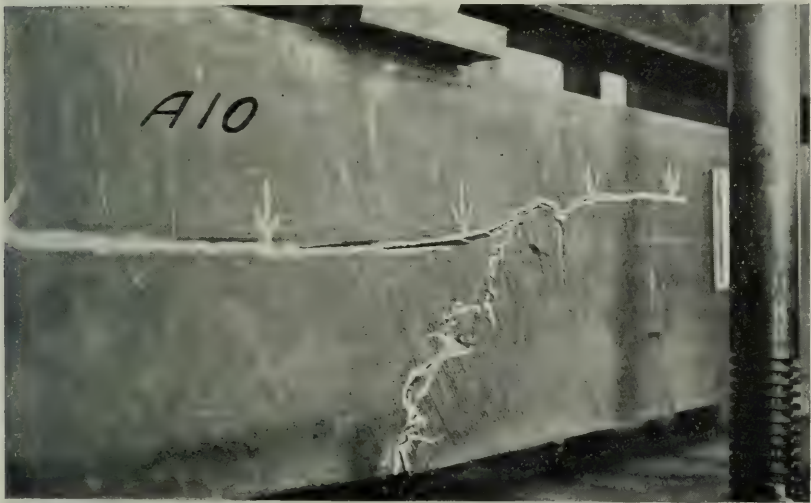
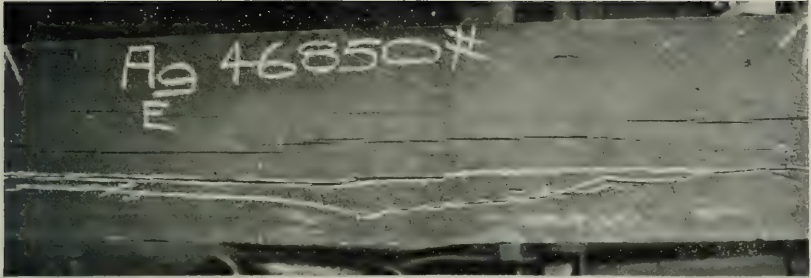


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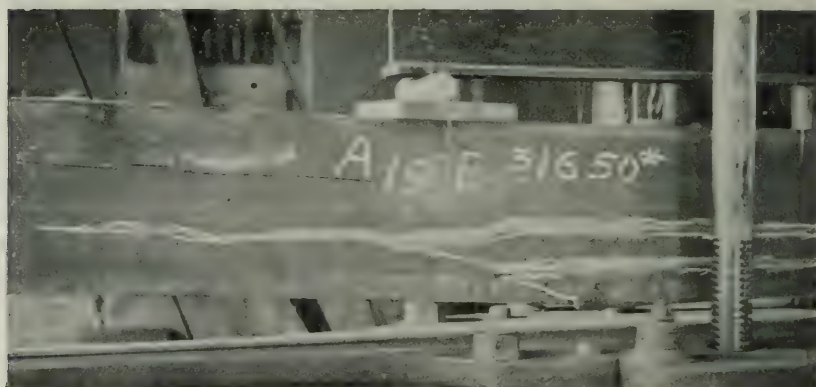
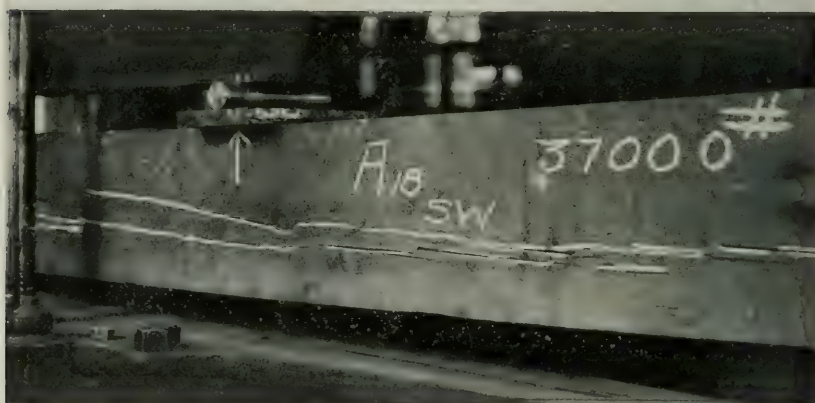
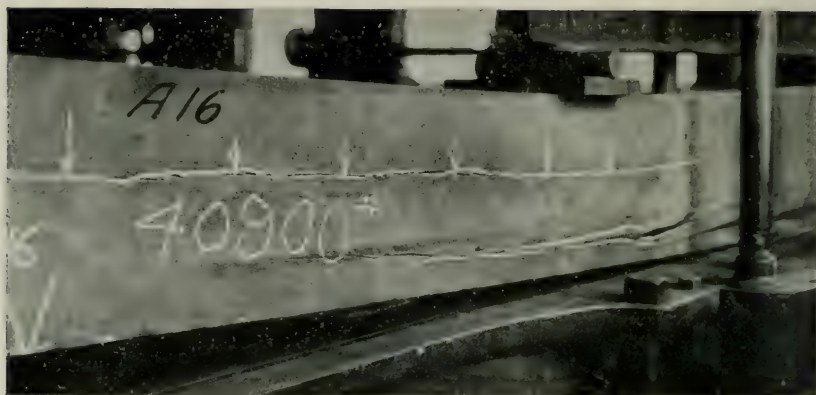


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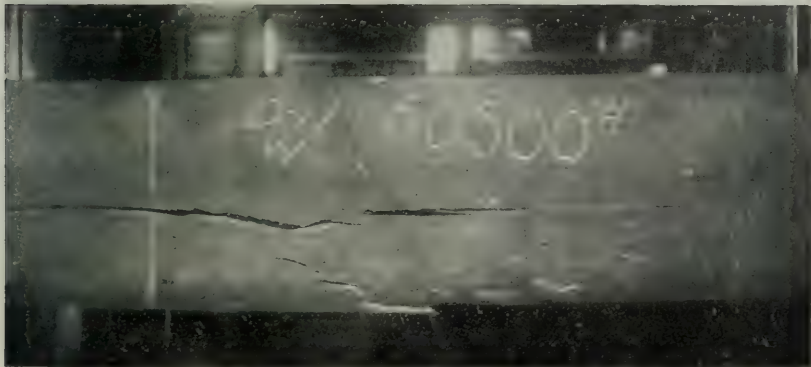
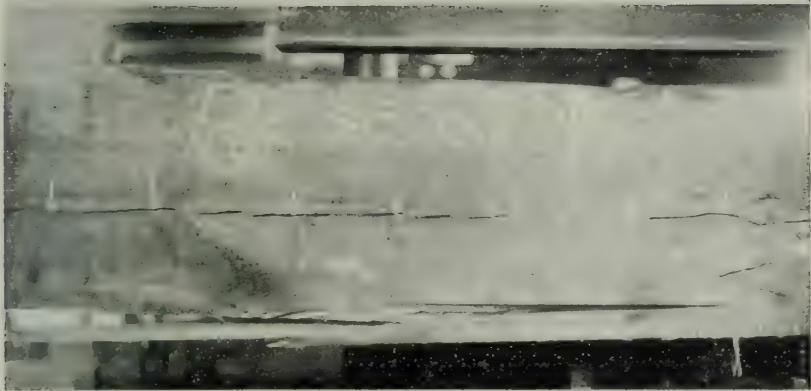
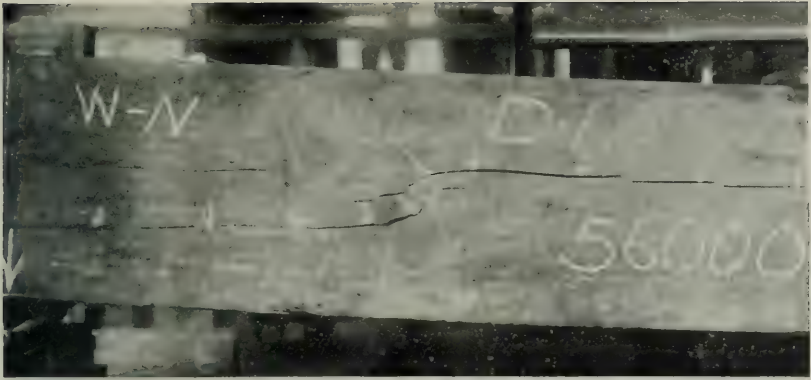


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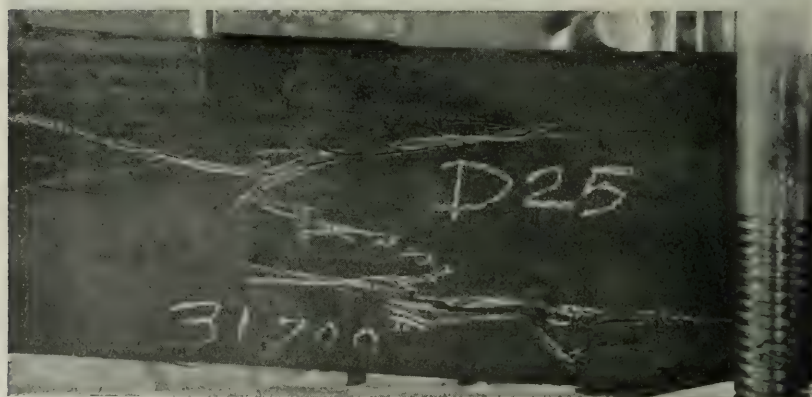
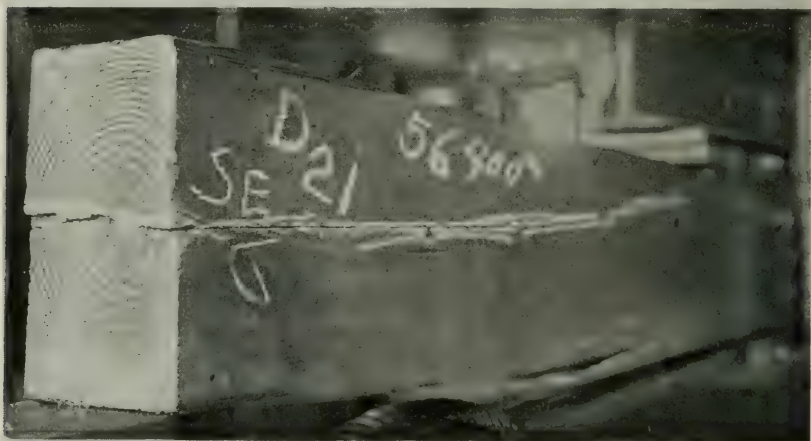
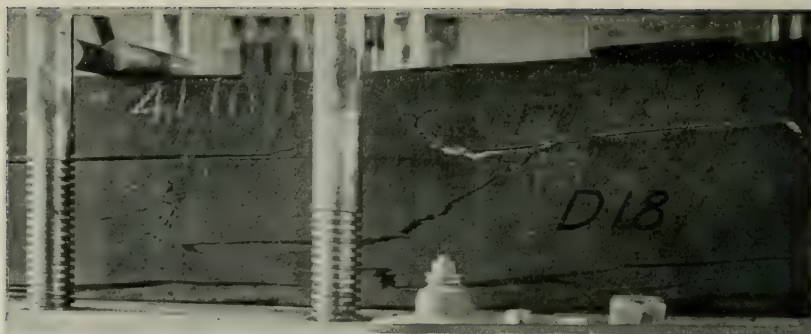


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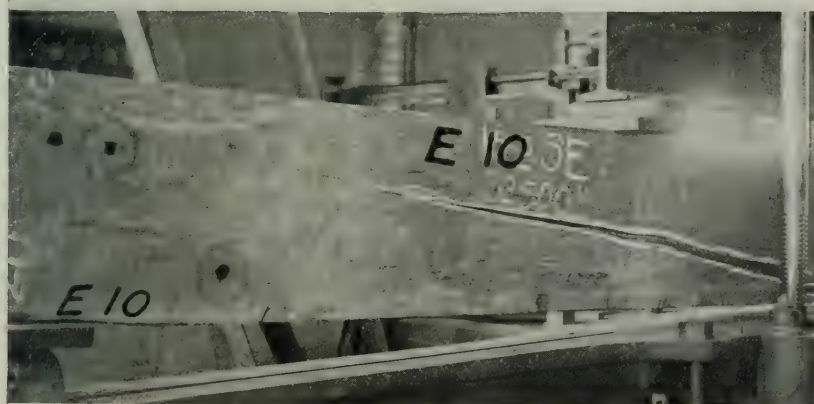
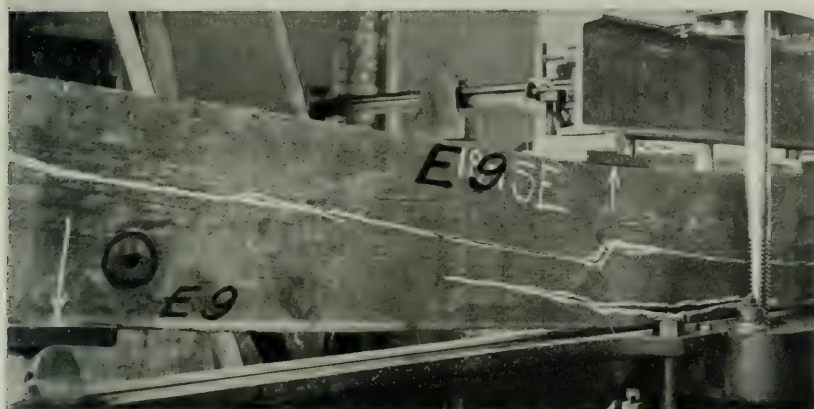
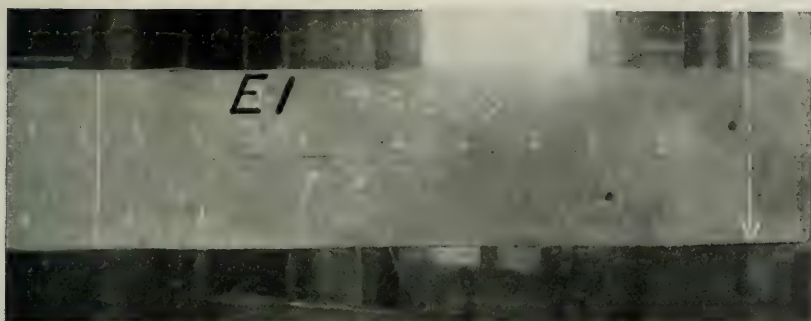


PLATE 6. VIEWS OF BEAMS AFTER FAILURE.

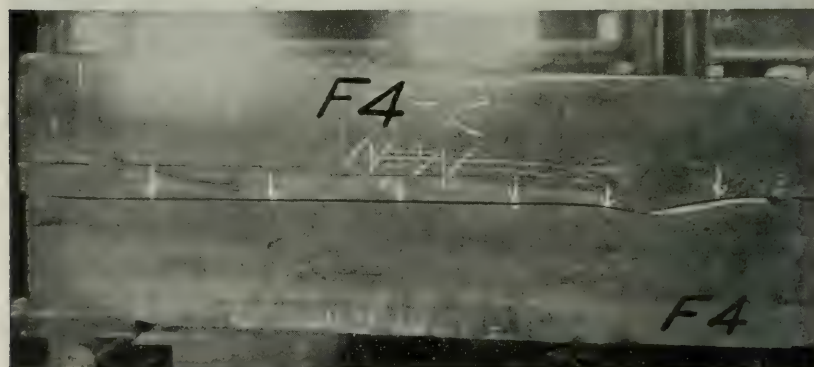
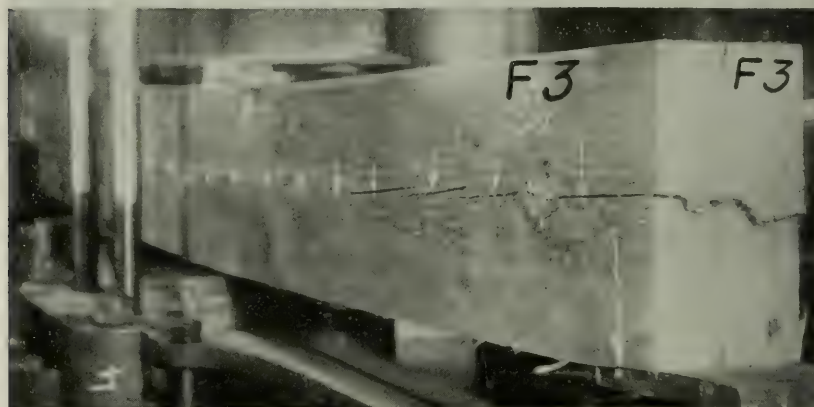
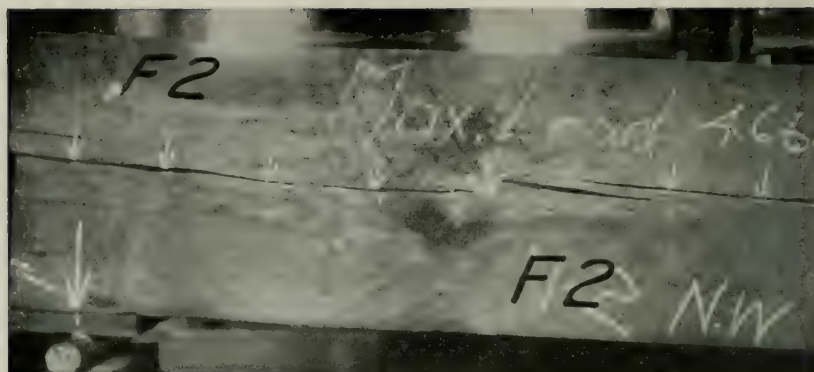


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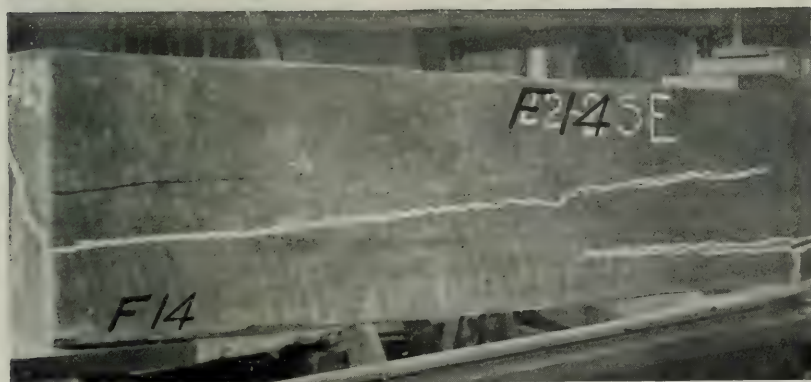
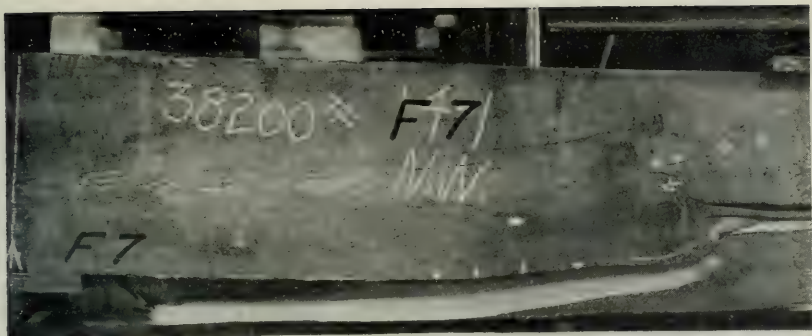


PLATE 8. VIEWS OF BEAMS AFTER FAILURE.

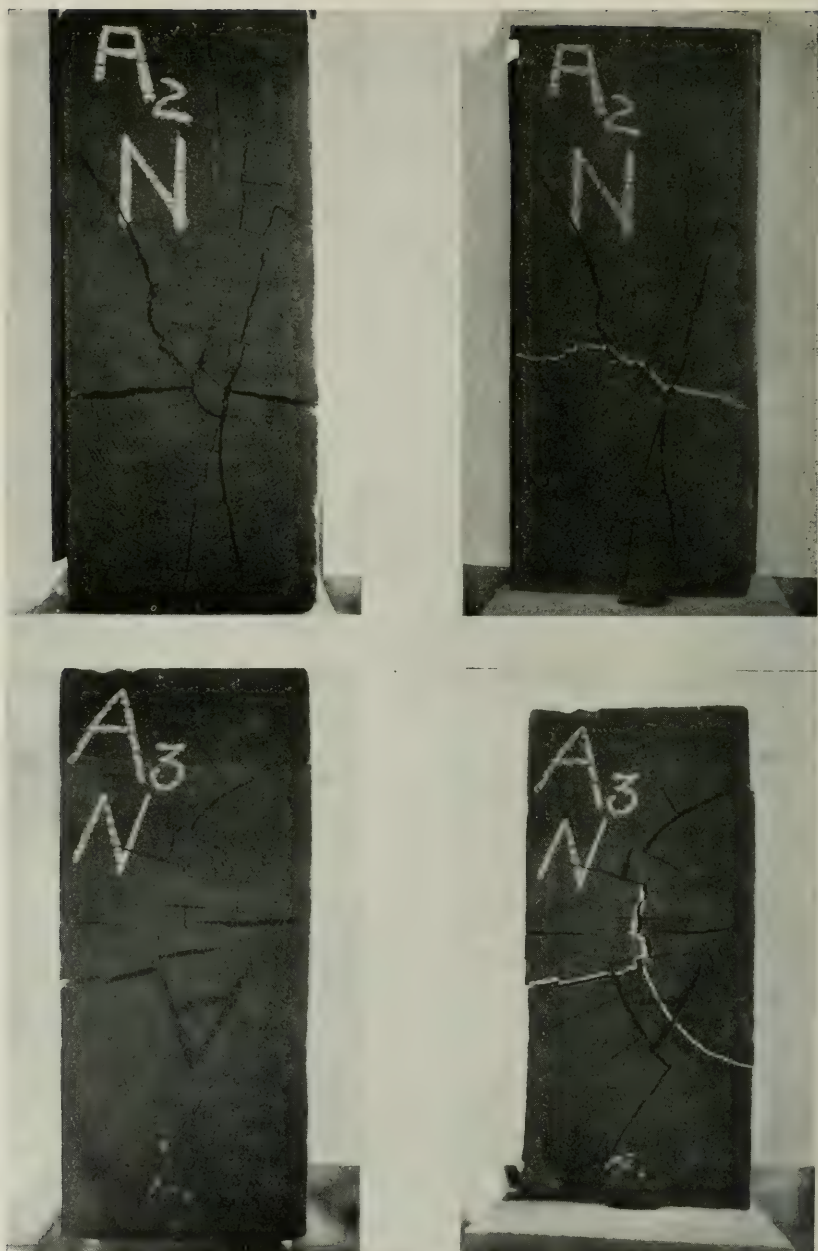


PLATE 9. VIEWS OF ENDS OF BEAMS BEFORE AND AFTER FAILURE.

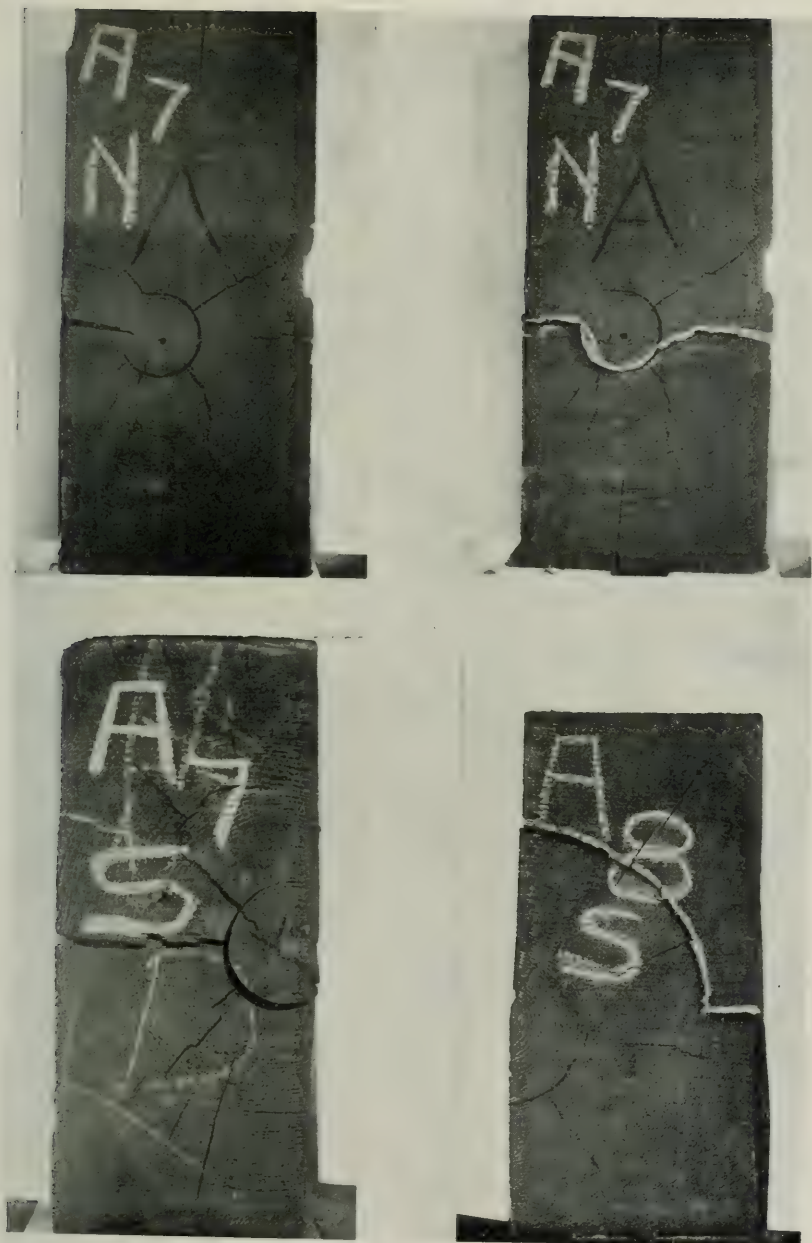


PLATE 10. VIEWS OF ENDS OF BEAMS BEFORE AND AFTER FAILURE.

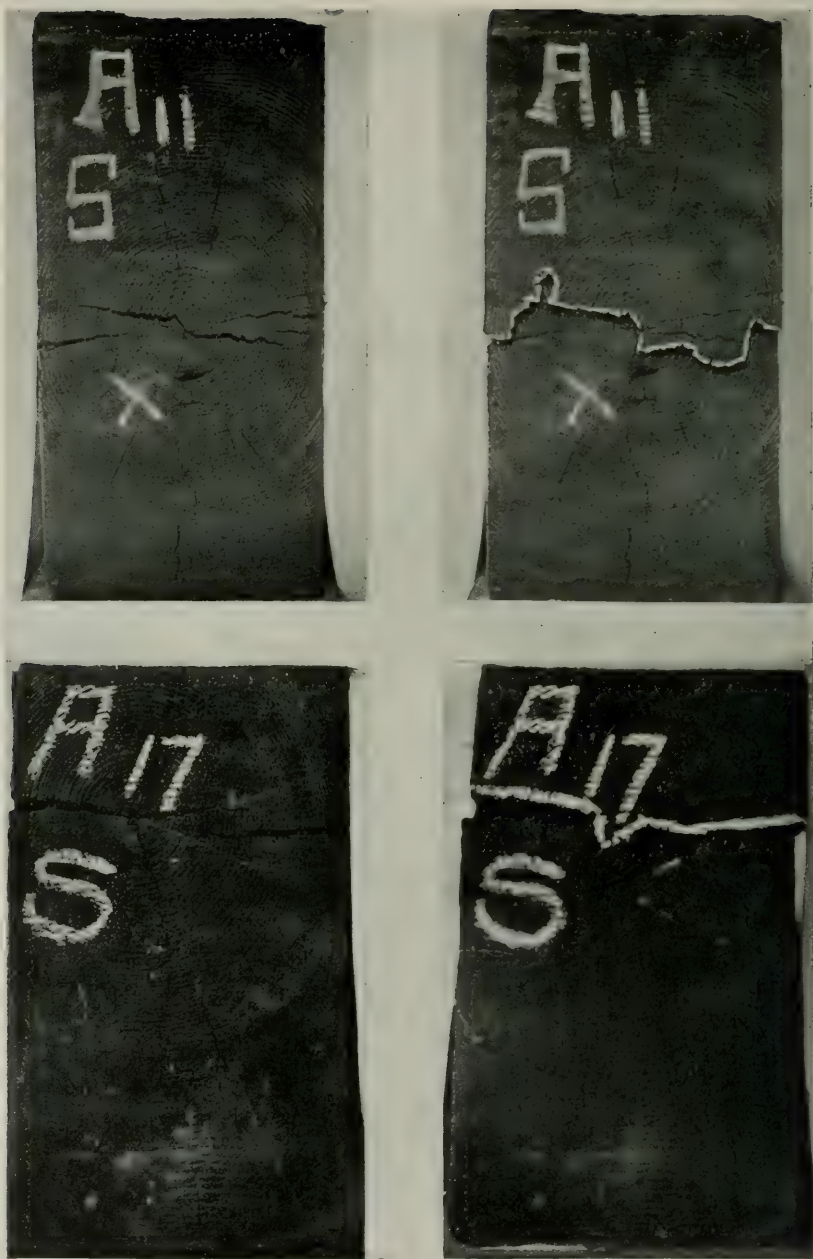


PLATE 11. VIEWS OF ENDS OF BEAMS BEFORE AND AFTER FAILURE.

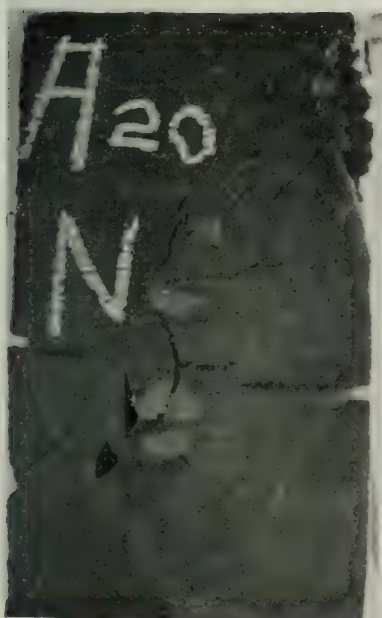
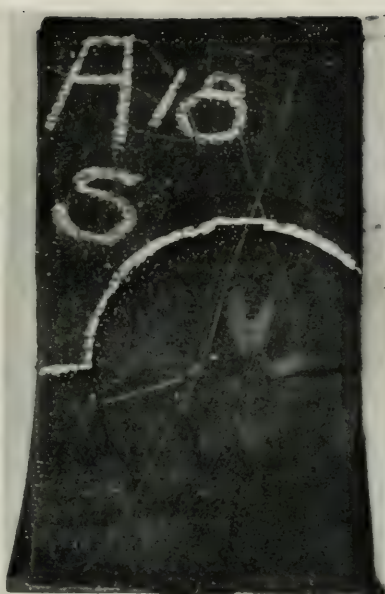
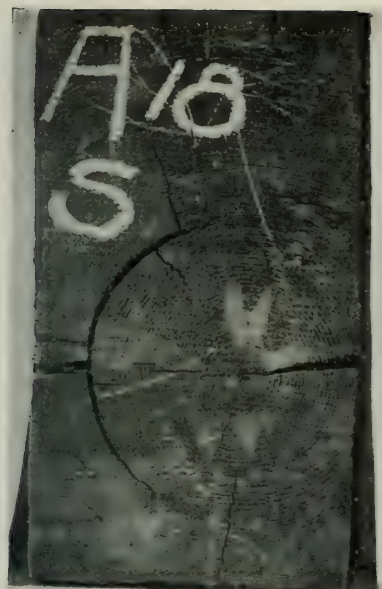


PLATE 12. VIEWS OF ENDS OF BEAMS BEFORE AND AFTER FAILURE.

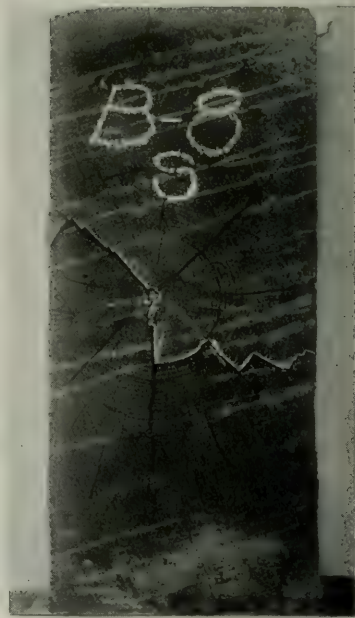
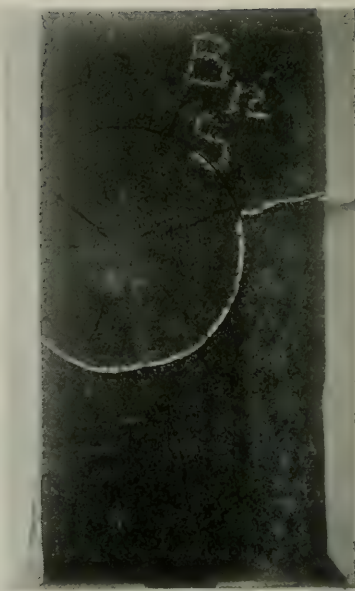


PLATE 13. VIEWS OF ENDS OF BEAMS AFTER FAILURE.

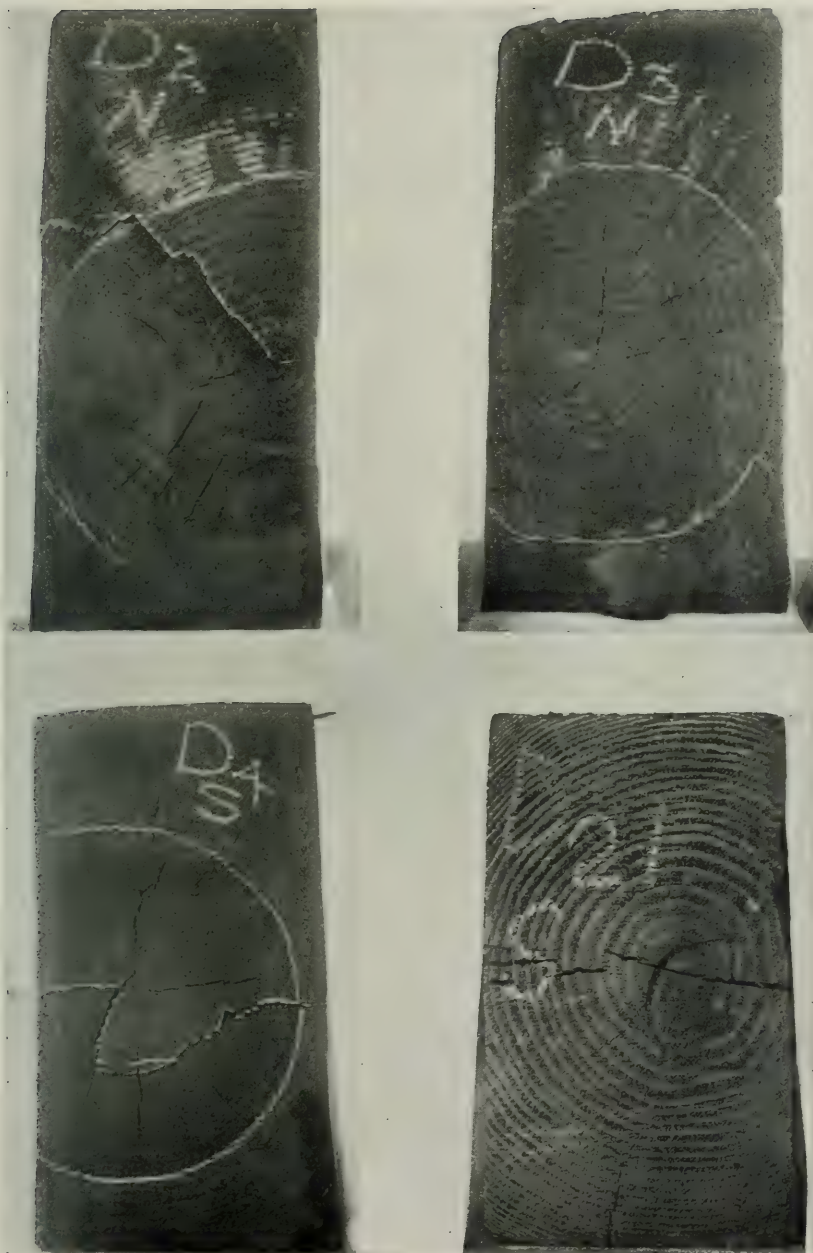


PLATE 14. VIEWS OF ENDS OF BEAMS AFTER FAILURE.

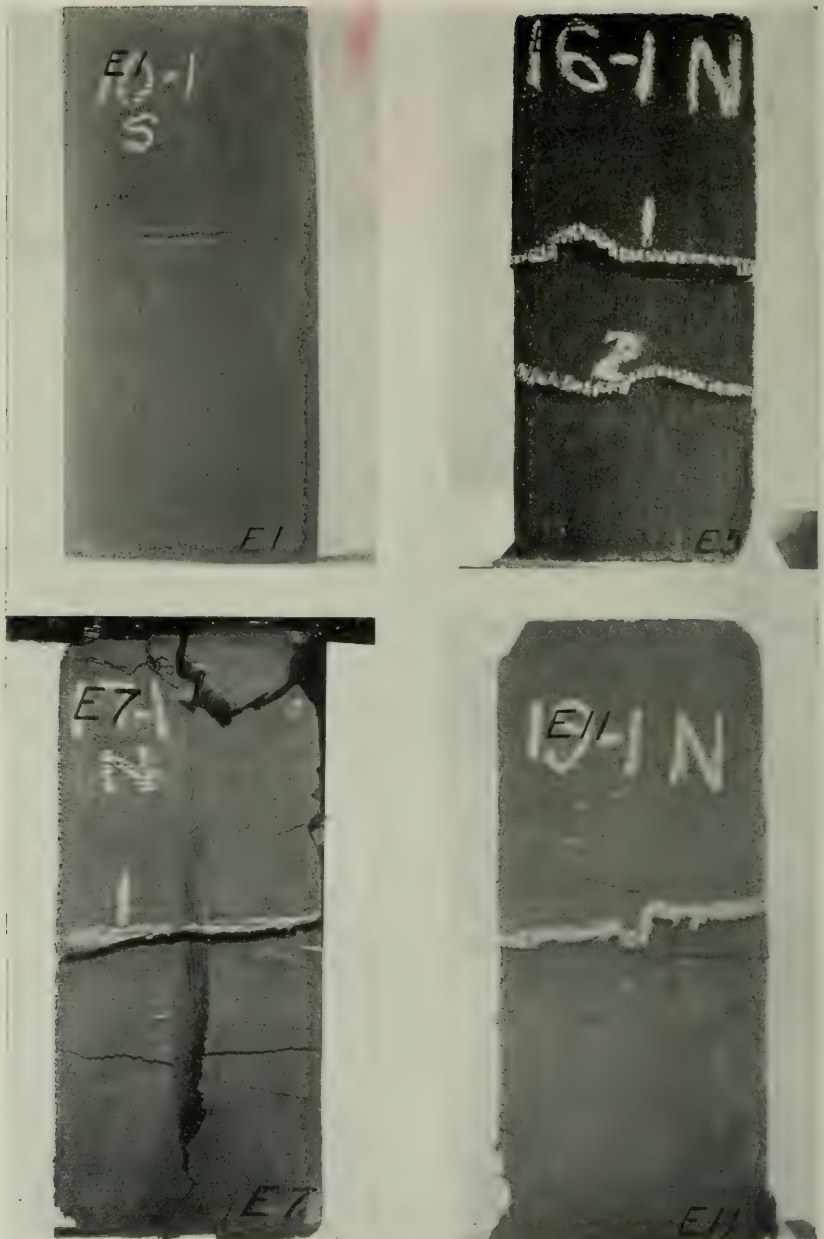


PLATE 15. VIEWS OF ENDS OF BEAMS AFTER FAILURE.

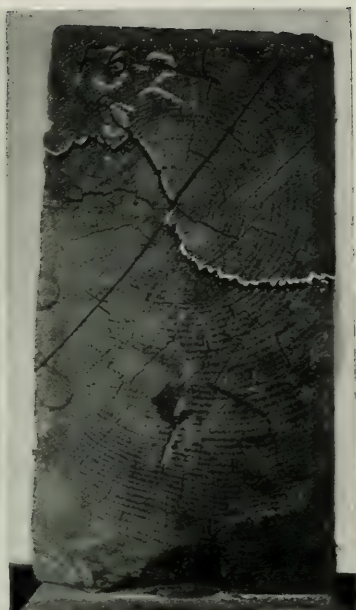
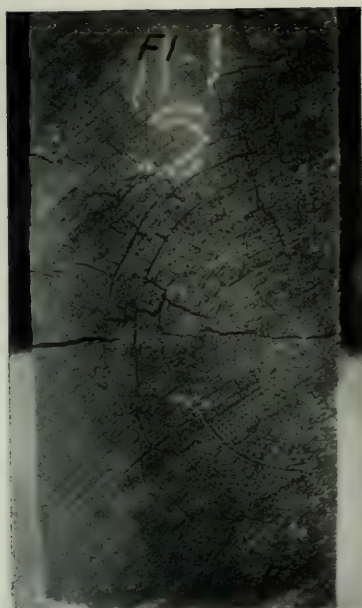


PLATE 16. VIEWS OF ENDS OF BEAMS BEFORE AND AFTER FAILURE.

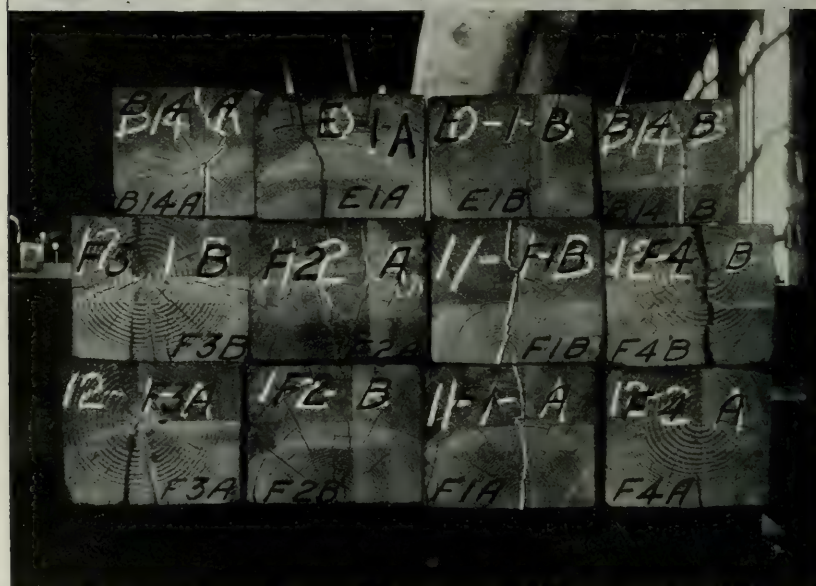
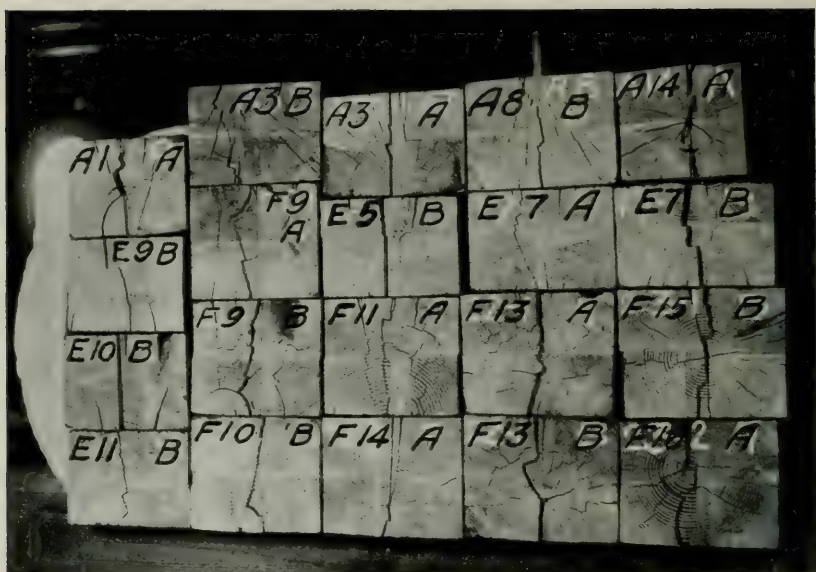


PLATE 17. VIEWS OF SHEAR BLOCKS AFTER FAILURE.

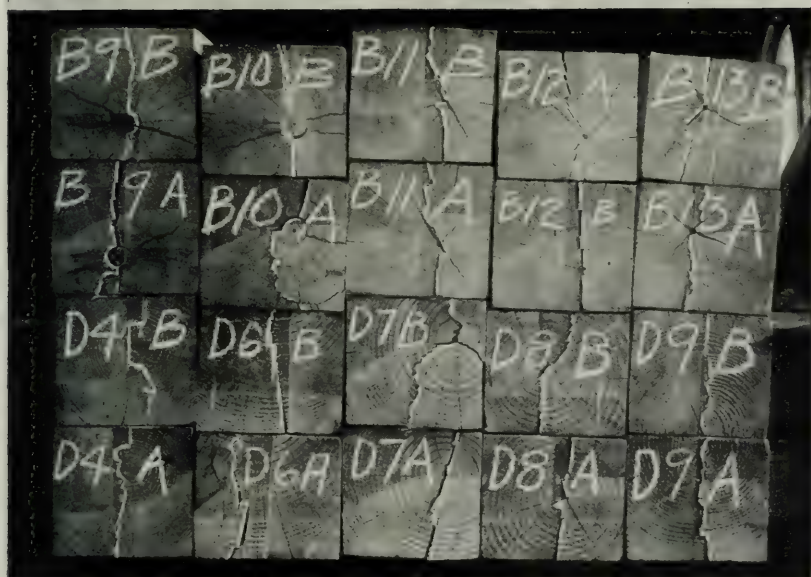
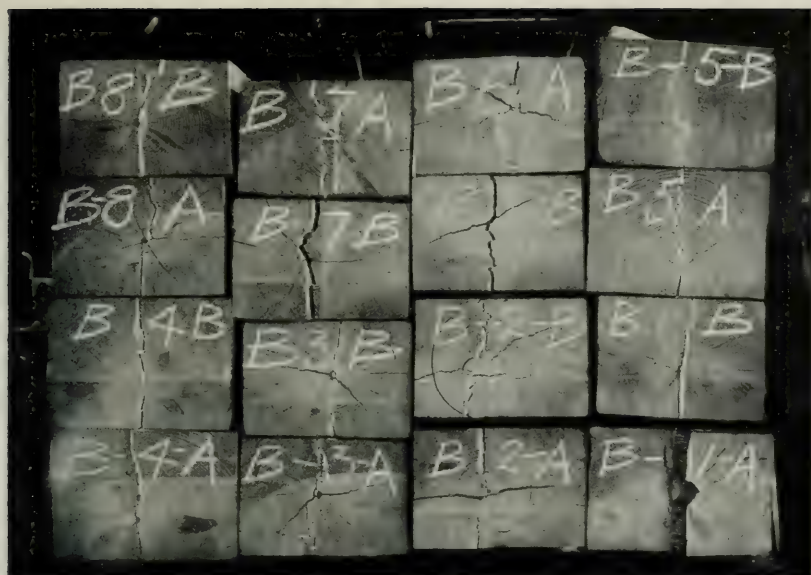


PLATE 18. VIEWS OF SHEAR BLOCKS AFTER FAILURE.

UNIVERSITY OF ILLINOIS
ENGINEERING EXPERIMENT STATION

BULLETIN No. 41

DECEMBER 1909

TESTS OF TIMBER BEAMS

BY ARTHUR N. TALBOT, PROFESSOR OF MUNICIPAL AND SANITARY
ENGINEERING AND IN CHARGE OF THEORETICAL
AND APPLIED MECHANICS

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TESTS OF TIMBER BEAMS.

I. INTRODUCTION.

1. *Preliminary.*—Although timber has long been an important structural material, it is recognized that our knowledge of its structural properties is still quite inadequate, even though the work of recent years has added much valuable information. Generally speaking, the values for the strength of the various species of wood given in engineering text-books have been based on tests of small pieces taken from what may be considered to be selected wood, and until recently the number of tests on sticks of structural sizes has been very small. In view of the growing scarcity of timber and the necessity of utilizing the poorer grades, as well as because the competition with other structural materials is increasing, it would seem that the need for fuller information on the structural properties of timber is a matter of importance. It was with the view of adding data on the properties of timber in the form of stringers as used in many railroad structures and of the quality which may be expected to be found under the ordinary methods of purchase by railroad companies and others that this series of tests was undertaken.

The timber stringers were 8 x 16 in. x 15 ft. to 7 x 12 in. x 14 ft. in size. One hundred and twelve sticks were tested. The woods included longleaf pine, shortleaf pine, loblolly pine, and Douglas fir. A number of creosoted pine stringers were among those tested. The stringers were tested as beams with the load applied equally at the one-third points of the span length. The dimensions of the sticks were such as to bring out the strength of timber in horizontal shear. The influence of such defects as knots, seasoning checks, and wind shakes may be seen in the results. Minor test pieces were cut from the stringers and their flexural and shearing strength determined, and the relation of the properties of the smaller test pieces to the full-size stringers may be studied. It will be seen that the data of the tests have a bearing upon the properties of timber stringers under the conditions of ordinary purchase and practical service.

2. *Acknowledgment.*—The tests were made possible through the co-operation of the Illinois Central Railroad Company, and the Chicago, Rock Island and Pacific Railroad Company, which furnished the stringers. Mr. R. E. Gaut, Engineer of Bridges, and Mr. E. H. Bowser, Chief Timber Inspector, of the Illinois Central Railroad, were instrumental in selecting and providing the pine timber, and acknowledgment is made of their interest and helpfulness. Mr. J. B. Berry, Chief Engineer, Chicago, Rock Island and Pacific Railroad, furnished the fir stringers for these tests. The tests were carried on as work of the Engineering Experiment Station. Mr. W. R. Robinson has given helpful assistance in putting the results into form.

3. *Notes on Timber Testing.*—As already stated, the values for the strength properties of timber most generally cited in text-books and pocket-books in the past were evidently determined from small selected sticks. One text-book gives the strength of yellow pine in tension as 15 000 lb. per sq. in., in compression 9000 lb. per sq. in., and in longitudinal shear 500 lb. per sq. in. An engineers' pocket-book gives the value of the modulus of rupture of yellow pine as 15 300 lb. per sq. in. Lanza* cites several authorities as giving mean values of the modulus of rupture of yellow pine from 9000 to 15 000 lb. per sq. in., but the results of his own tests he reports as averaging 7500 lb. per sq. in. for modulus of rupture and 224 lb. per sq. in. for longitudinal shear and he very emphatically shows that the strength of commercial timber is much lower than usually quoted. Johnson* gives for yellow pine 9000 lb. per sq. in. in compression, 13 000 lb. per sq. in. in cross breaking and 600 lb. per sq. in. in longitudinal shear, while for loblolly pine, values of the corresponding strengths are 7000, 10 000, and 400 lb. per sq. in. The handbook of the Southern Lumber Manufacturers' Association (1904) gives for longleaf pine the following strengths: tension 15 200 lb. per sq. in., compression 6850 lb. per sq. in., cross breaking 10 900 lb. per sq. in., longitudinal shear 706 lb. per sq. in.; for shortleaf pine the corresponding values are 13 400, 5900, 9230, and 688; and for loblolly pine 14 400, 6500, 10 100, and 690. These values are stated to be based upon 15% moisture content on beams from which defective pieces were excluded and to give fairly well the range of strength of commercial timber. With such illustrations as these in mind, it

*Applied Mechanics, by G. Lanza. The Materials of Construction, by J. B. Johnson.

does not seem strange that engineers may hold to higher values for the strength of commercial timber than later tests have shown to be tenable. A comparison of the foregoing values with the tests herein recorded shows that these tests gave strengths much lower than the values which are commonly cited.

The tests made on full-size pieces (structural sizes) have shown that the defects commonly found in commercial timber have a considerable influence on their strength, and it seems reasonable to expect that tests should be made on sticks of the size which is to be used and that the sticks should be selected in a manner similar to the way in which they will be chosen in the market, if it is desired to establish their strength under commercial conditions. Some of the earlier tests on so-called full-size sticks were not on structural sizes, but a number of series of tests on large sticks have been conducted which gave valuable information. The tests conducted by the Division of Forestry under the direction of Professor Johnson are reported in U. S. Forestry Circulars No. 12 and 15. Professor Lanza's extensive series of tests includes important and valuable data; the report of these may be found in Lanza's *Applied Mechanics*. The more recent work of the Bureau of Forestry on large-size beams under the general direction of Professor Hatt has also given valuable information. This is reported in the circulars of the Forest Service. An important series of tests on white pine beams by Onward Bates, reported in the *Transactions of the American Society of Civil Engineers*, vol. 23, may also be mentioned.

A valuable bibliography of timber tests and of the properties of timber may be found in *Transactions of the American Society of Civil Engineers*, vol. 54, part F, page 87. Important discussions of the subject of timber and timber tests may also be found in the same volume and in vol. 51. Bulletin No. 12 of the Division of Forestry, U. S. Department of Agriculture, gives valuable discussions on the strength and working strength for application to timber trestles. Valuable matter is to be found in the bulletins of the American Railway Engineering and Maintenance of Way Association. In Bulletin No. 85* of this association Professor Hatt gives the results of the recent work on timber tests of the Forest Service. In Bulletin No. 107* of the same association, the

* See also *Proceedings of American Railway Engineering and Maintenance of Way Association*, vol. 8, pp. 409 and 417, and vol. 10, p. 533.

Committee on Wooden Bridges and Trestles reports important data on the properties of timber and on the practice of the railroads of the country.

4. *Formulas and Properties.*—The analysis on which the usual formulas for beams are based assumes a homogeneous material and a constant modulus of elasticity. These assumptions are fairly well met in such a material as steel within its elastic limit. Timber is not so uniform and homogeneous. The usual conception of a homogeneous bundle of fibers parallel with each other throughout the length of the beam is not entirely correct. The wood differs in different parts of the section,—heart wood and sap wood differ in their proportions and their distribution, even

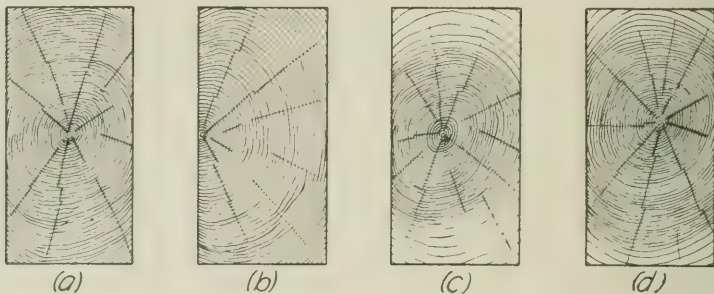


FIG 1. DISTRIBUTION OF HEARTWOOD AND SAPWOOD OVER SECTION.

in different sticks of the same species (Fig. 1). As the sap wood and the heart wood are of different degrees of stiffness and as the relative amount of spring wood and summer wood varies also, it is apparent that the modulus of elasticity of the material will vary in different parts of a section and also that it will vary from section to section of the beam. The condition of the grain will also affect the action of the beam; thus the presence of cross grain will modify the distribution of the internal stresses. Presence of knots may change the position of the neutral axis as well as reduce the amount of effective fibers available for flexural strength. All such variations produce a distribution and an amount of stress which differ from the results obtained by ordinary beam analysis. An important feature in the strength of timber is that its resistance to longitudinal or horizontal shear is relatively low even in good timber. The presence of shakes and seasoning checks reduces the horizontal shearing strength and modifies the distribu-

tion of the stresses over the section. It seems evident, then, (a) that the ordinary formulas when applied to timber must be considered to be largely empirical; and (b) that tests of full-size sticks are necessary to obtain working values for the timber used.

The derivation of the usual formulas for beams may be found in the standard text-books on mechanics of materials. The ordinary formula for resisting moment for a beam of rectangular cross section is

$$M = \frac{1}{6} f b d^2 \dots \dots \dots (1)$$

where f is the unit-stress or fiber stress at the top or bottom of the section, b is the width of the beam, and d its depth. In the principal tests herein described, the load was applied equally at the one-third points of the span length, and the maximum bending moment due to the applied load is therefore $\frac{1}{8} Wl$, where W is the total load applied and l is the span length. The formula for the deflection at the center of a beam loaded at the one-third points is $\frac{23}{1296} \frac{Wl^3}{EI}$, where E is the modulus of elasticity applicable

to flexure and I is the moment of inertia of the cross-section. In these formulas the effect of the deformations produced by horizontal shear is not taken into consideration.

In the discussion of shearing stresses, it should be noted, to begin with, that the intensity of the shearing stress at any point in a section (i. e., the shearing unit-stress) is the same for the vertical shear and for the horizontal shear. The formula for the vertical shearing unit-stress at the neutral axis and also for its equal, the horizontal or longitudinal shearing unit-stress at the same point, is

$$v_0 = \frac{3}{2} \frac{V}{bd} \dots \dots \dots (2)$$

where V is the total external vertical shear on the given section. In the case of the manner of loading above referred to, if we neglect the weight of the beam, the external vertical shear V is constant from the support to the load point and equal to one-half of the load; and it is zero between the load points.

Above and below the neutral axis the vertical shearing unit-stress, and therefore the horizontal shearing unit-stress, is given by the formula

$$v = \frac{3}{2} \frac{V}{bd} \left[1 - \left(\frac{z}{\frac{1}{2}d} \right)^2 \right] = v_0 \left[1 - \left(\frac{z}{\frac{1}{2}d} \right)^2 \right] \dots \dots \dots (3)$$

where z is the distance above or below the neutral axis. The var-

iation of the intensity of the shearing stress throughout a vertical section (applicable to both vertical and horizontal shearing stress) is illustrated in Fig. 2(a). It is seen that the decrease in stress is not very great over the middle third of the depth of the beam.

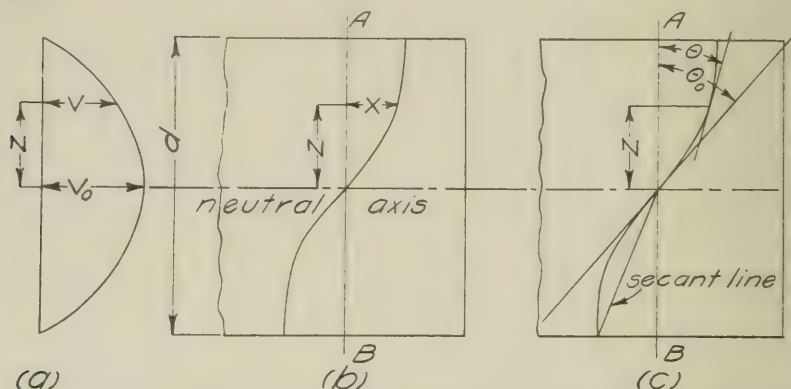


FIG. 2. DISTRIBUTION OF SHEARING STRESS AND MOVEMENT OF FIBER DUE TO HORIZONTAL SHEAR.

For convenience and conciseness of expression, the term fiber stress will be used in this bulletin to mean the calculated compressive or tensile unit-stress at the top or bottom of the beam for a section having the maximum bending moment, denoted by f in equation (1). The term elastic limit will be used to mean the calculated fiber stress at the elastic limit. The term horizontal shearing stress will be used to mean the shearing unit-stress at the neutral axis, v_0 , for a section having the maximum external vertical shear. Further, the formulas will be used beyond the elastic limit of the beams, where they give apparent or empirical values of the stresses.

An effect of horizontal shearing stress is to cause a distortion of the section from a straight-line section, as though the fibers had moved longitudinally. In a material like timber in which the modulus of elasticity against longitudinal shear is relatively small, this movement may be expected to be greater than in a homogeneous material or in one having a higher modulus of elasticity. Although the resistance to shear prevents the sliding which occurs when several boards are piled one above another and flexure applied, yet a vertical line drawn across a beam will be found to vary from a straight line after a load is applied. If, now, the

beam fails by horizontal shear the upper portion of the beam at the end will project beyond the lower as shown in the beams in Plate 7 (frontispiece), and the failure will extend some distance along the length of the beam.

It may be shown that the amount of the horizontal movement x of a point on the beam with reference to a straight line, (see Fig. 2 (b), the line of reference AB considered to remain normal to the elastic curve at the neutral axis), is given by the equation

$$x = \frac{3}{2} \frac{1}{bdE} \left[z - \frac{1}{3} \frac{z^3}{(\frac{1}{2}d)^2} \right] = \frac{v_0 z}{E} \left[1 - \frac{1}{3} \left(\frac{z}{\frac{1}{2}d} \right)^2 \right] \dots \dots (4)$$

where E is the modulus of elasticity for horizontal shear and z is the distance of the point from the neutral axis. It may be noted that this E is much smaller in timber than the E used in the formula for determining the deflection of beams. The form which a section takes with reference to the normal to the elastic curve is shown by the curve in Fig. 2 (b). The total longitudinal movement of a point at the top with reference to a point at the bottom is, by the foregoing formula, $\frac{2}{3} \frac{v_0 d}{E}$. The slope which the curve at any point makes with the normal already referred to (Fig. 2 (c)), is given by the equation

$$\tan \Theta = \frac{v}{E} \dots \dots \dots (5)$$

where Θ is the slope of the curve with the reference line, and v is the unit-shear at the same point. For a point at the neutral axis the slope of the curve is $\tan \Theta_0 = \frac{v_0}{E}$. At the top and bottom the direction of the curve is parallel with the reference line. The slope of the secant line through the top and bottom of the curve is approximately two-thirds of the slope of the curve at the neutral axis, since for small angles the tangent and angle are equal. The value of E for horizontal shear applicable in these formulas has not been established so far as known. It is evident that the total amount of horizontal movement in the stringer of ordinary size is very small.

It may be anticipated that the properties of timber lack uniformity and that for any given grade or kind of timber they will vary considerably with the individual stick. Tests may be

expected to be of service in getting a range of results, in finding methods of failure most likely to occur, and in indicating what to look out for in service.

II. TEST PIECES AND METHOD OF TESTING.

5. *The Timber Stringer Series.*—The tests of full-size timber stringers for convenience of discussion are classified in six series: A, B, C, D, E, and F. These series are not expressive of divisions of the investigation, but were adopted during the development of the work. Table 1 gives data of the materials, size of sticks, condition of the timber, etc. The sticks were generally 14 ft. long, though the fir stringers came in lengths of 32 ft. Obstacles in the way of shipment and of making tests immediately upon receipt of the timber rendered it impracticable to carry out the original plan in every way and not all the conditions and determinations first planned were included in the final tests. The first tests (Series C, tested 1905-6) were made to give a comparison of the properties of creosoted and untreated timber of shortleaf pine and loblolly pine under the conditions of treatment then in use by the Illinois Central Railroad. The details of the treatment and the

TABLE 1.

CLASSIFICATION OF TIMBER STRINGERS.

Series	Wood	No. of Pieces	Condition	Nominal Size in. x in. x ft.	Seasoning months
C	Shortleaf pine	4	Untreated	7 x 16 x 14	12
C	Shortleaf pine	4	Creosoted	7 x 16 x 14	10*
C	Shortleaf pine	4	Creosoted	7 x 16 x 14	10*
C	Loblolly pine	4	Untreated	7 x 16 x 14	12
C	Loblolly pine	4	Creosoted	7 x 16 x 14	10*
C	Loblolly pine	4	Creosoted	7 x 16 x 14	10*
A	Longleaf pine	8	Untreated	7 x 16 x 14	18
A	Longleaf pine	6	Untreated	7 x 14 x 14	18
A	Longleaf pine	6	Untreated	7 x 12 x 14	12
B	Longleaf pine	8	Untreated	7 x 16 x 14	4
B	Longleaf pine	6	Untreated	7 x 14 x 14	4
D	Loblolly pine	8	Untreated	7 x 16 x 14	6
D	Loblolly pine	6	Creosoted	7 x 16 x 14	2*
D	Loblolly pine	6	Untreated	7 x 14 x 14	6
D	Loblolly pine	6	Creosoted	7 x 14 x 14	2*
E	Old Douglas fir	12	Untreated	7 x 16 x 15	11 years
F	New Douglas fir	16	Untreated	8 x 16 x 15	Partly seasoned

*Time of seasoning at treatment. Creosoted beams of Series C were tested about two months after treatment; those of Series D seven months after treatment.

amount of oil used are given in Table 2. The amount of the horizontal shearing strength developed in the many beams failing by horizontal shear in this series was so small that it was thought best to make tests on beams of several depths to find whether a

TABLE 2.
DATA OF TREATMENT OF TIMBER.

Designation	Steam		Vacuum		Creosote			
	Time hr. min.	lb. per sq. in.	Time hr. min.	Inches	Time hr. min.	lb. per sq. in.	Temp. F°	lb. per cu. ft.
C 5—C 8	4 30	35	2 00	24.5	0 25	88	170°	6.2
C 9—C 12	4 30	35	2 00	24.5	2 00	100		7.9
C 17—C 20	4 36	35	2 00	24.5	0 25	88	170°	17.5
C 21—C 24	4 30	35	2 00	24.5	2 00	100		14.9
D 15—D 26	5 00	30	2 00	24	1 30	125		16.0
M 3 x 3 in.	5 00	30	2 00	24	1 30	125		20.3
M shear	5 00	30	2 00	24	1 30	125		10.6
N 3 x 3 in.	5 00	30	2 00	24	1 30	125		17.2
N shear	5 00	30	2 00	24	1 30	125		19.3

smaller depth of beam would permit the full value of the modulus of rupture of the wood to be developed. At the same time the effect of pronounced seasoning checks and of large knots was taken up and also a further comparison of treated and untreated loblolly pine. These stringers, furnished by the Illinois Central Railroad, and tested in July and August, 1906, December, 1906, and January, 1907, are included in Series A, B, and D. Two conditions of seasoning were included in the longleaf pine stringers,—one a period of about 18 months in Series A and the other one of about 4 months in Series B. Series E and F comprised Douglas fir stringers furnished by the Chicago, Rock Island and Pacific Railway. The stringers in Series E had seen service for 11 years in a trestle in Nebraska and this series may be expected to represent the degree of seasoning and seasoning checks attained by such wood in service. This timber was as well seasoned as may be expected under ordinary atmospheric conditions. Series F was unused Douglas fir stringers partly seasoned and may be expected to represent the condition of such timber when first put into service. Although no relation between the quality of the wood in the two sets of stringers is known, the results will furnish some comparison between the properties of such stringers under two sets of conditions. These fir stringers came in lengths of 32 ft. and

were cut in two before testing. In the designation, an odd number and the succeeding even number represent two pieces from one stick. In Series A, B, and D, a few sticks had been selected having knots of such size and in such a position that these defects would, in any thorough-going inspection, have been cause for rejection. These were included with a view of finding the effect of such marked defects. The shallower stringers in Series A, B, and D were cut down from 16-in. sticks.

In Table 1 the time of seasoning of the untreated stringers at test is given. The stringers were in general left in the yard until shipment and upon reaching the laboratory were piled and stored in such a way that they continued to season slowly. For the creosoted sticks the time of seasoning at treatment is given in Table 1. It is not expected that the time which elapsed after treatment affected in any marked way the properties of the wood. As already stated, the old Douglas fir stringers were well seasoned. As noted further on, the results of the moisture determinations are given in Table 4 and the method of determination is described under "8. Moisture Determination."

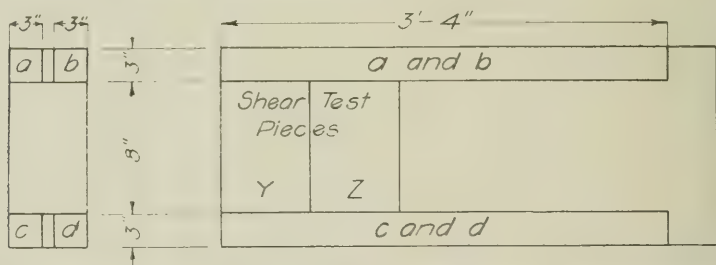


FIG. 3. LOCATION OF MINOR TEST PIECES IN FULL-SIZE STRINGERS.

6. *Minor Test Pieces.*—After the cross-bending test of the full-size sticks had been made, minor test pieces were cut from the stringers in Series A, B, D, E, and F for further test. These minor test pieces included shear test pieces and small test beams. The classification of the minor test pieces is given in Table 3. The position of these test pieces in the stringer and their designation are shown in Fig. 3. The shear test pieces (y and z, Fig. 3.) were taken from near the middle of the depth of the stringer. If the stringer had failed in horizontal shear at one end, the shear test piece was cut from the other end. The shear test piece was the full thickness of the stringer and about 8 to 10 in. wide and

12 in. long. It was cut so as not to contain knots, but it did include seasoning checks which existed in the middle half of the depth of the stringer and as such is more nearly representative of the shearing strength of the full-size stick than are the small test pieces which have generally been used hitherto in the deter-

TABLE 3.

CLASSIFICATION OF MINOR TEST PIECES.

These test pieces were cut from the tested stringers.

The small test beams were 3 x 3 x 40 in. The shear blocks were 7 x 10 x 12 in.

Series	Wood	Test Pieces	No. of Pieces	Condition	Seasoning months
A	Longleaf pine	Beam	80	Untreated	18
A	Longleaf pine	Shear block	33	Untreated	18
B	Longleaf pine	Beam	51	Untreated	4
B	Longleaf pine	Shear block	28	Untreated	4
D	Loblolly pine	Beam	50	Untreated	6
D	Loblolly pine	Shear block	26	Untreated	11
D	Loblolly pine	Beam	47	Creosoted	2
D	Loblolly pine	Shear block	22	Creosoted	2
E	Old Douglas fir	Beam	47	Untreated	11 years
E	Old Douglas fir	Shear block	26	Untreated	11 years
F	New Douglas fir	Beam	46	Untreated	Partly seasoned
F	New Douglas fir	Shear block	20	Untreated	

mination of shearing strength. One hundred and fifty-five of these shear test pieces from Series A, B, D, E, and F were tested. The minor test beams, (a, b, c, and d, Fig. 3), of which there were three hundred and eleven, were cut from the four corners of one end of the stick. These pieces were usually 3 x 3 x 40 in. and were tested with a span of 36 in. They were sawed out and tested to give a comparison of the strength in cross bending of the wood at the top and bottom of the stringer with the strength developed in the full-size stick.

7. *Miscellaneous Test Pieces. Series M and N.*—Several stringers were cut up at the mill as shown in Fig. 4. In series M, all pieces were creosoted. In Series N (cut from 16-ft. stringers), the alternate pieces were treated by the creosoting process (the even numbers are creosoted and the odd numbers untreated). The statement of treatment is given in Table 2. The 4 x 4 x 42 in. pieces were cut to 3 x 3 x 40 in., and were tested as beams in the same way (usually 36-in. span) as were the small beams of the series of

minor test pieces. The shear test pieces were approximately 7 x 8 x 12 in. The creosoted pieces had been cut about three months at time of treatment and the untreated pieces about twelve months at time of test. One hundred and four shear blocks and 122 small test beams were tested in series M and N.

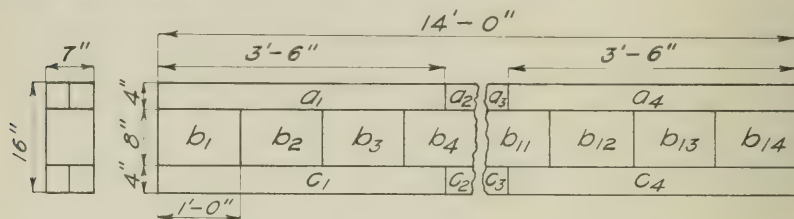


FIG. 4. LOCATION OF MISCELLANEOUS TEST PIECES.

8. *Moisture Determination.*—From each stringer after test a disc about 1 in. thick and the full cross-section of the stringer was cut about 4 ft. from one end. These discs were weighed immediately and then thoroughly dried in an oven at a temperature of about 180° F. for 24 hours, or more, until the loss of weight for the last 6 hours was less than 1 %. The results are given in Table 4. The moisture is unevenly distributed in a stick, varying throughout the length and section, but the results may be taken as indicative in a general way of the moisture condition of the sticks. Determinations were not made for Series C, M, and N.

9. *Cross-bending Tests of Stringers.*—The stringers were tested in cross bending on a 200 000-lb. Olsen beam-testing machine in the Laboratory of Applied Mechanics of the University of Illinois. The span was 13 ft. 6 in. except in Series E and F where it was 14 ft. 6 in. The beams rested on rocker supports which gave free longitudinal movement. Iron bearing plates 8 in. wide, 1 in. thick, and of a length greater than the width of the stringer were used to prevent the crushing of the wood at the supports. The load was applied equally at two points on the top of the beam, each one third the span length from the supports. Bearing plates like those before mentioned were used at the points of application of the load. The load was applied progressively to failure, a stop being made at the various loads to give the observers time to read the instruments. The head of the testing machine was run down at a speed of 0.17 in. per minute. This movement corresponds to an application of longitudinal or fiber deformation in

the extreme fiber at mid-span equal to 0.00056 in. per inch of length per minute for a 7 x 16-in. beam and 13½ ft. span.

TABLE 4.
MOISTURE CONTENT OF TEST PIECES.

Series A		Series B		Series D		Series D		Series E		Series F	
Des.	percent	Des.	percent	Des.	percent	Des.	percent	Des.	percent	Des.	percent
A 1	19.7	B 1	26.6	D 1	21.9	D 15	39.3	E 1	14.9	F 1	24.9
A 2	18.6	B 2	27.2	D 2	46.8	D 16	33.8	E 2	17.4	F 2	23.6
A 3	18.5	B 3	27.0	D 3	45.2	D 17	31.4	E 3	14.1	F 3	23.8
A 4	18.8	B 4	25.4	D 4	30.0	D 18	30.9	E 4	14.4	F 4	24.0
A 5	18.9	B 5	25.2	D 5	....	D 19	31.9	E 5	16.8	F 5	23.9
A 6	18.9	B 6	25.3	D 6	41.0	D 20	36.9	E 6	16.8	F 6	25.9
A 7	18.1	B 7	27.8	D 7	28.2	D 21	29.0	E 7	15.7	F 7	22.0
A 8	18.5	B 8	25.5	D 8	45.7	D 22	51.1	E 8	16.3	F 8	23.2
A 9	18.4	B 9	22.6	D 9	71.1	D 23	22.1	E 9	17.0	F 9	22.1
A 10	18.3	B 10	29.1	D 10	26.2	D 24	51.6	E 10	17.5	F 10	23.2
A 11	19.5	B 11	29.1	D 11	31.2	D 25	42.0	E 11	16.8	F 11	22.7
A 12	19.0	B 12	26.2	D 12	60.0	D 26	33.0	E 12	17.9	F 12	23.8
A 13	18.3	B 13	30.2	D 13	41.4					F 13	25.4
A 14	19.5	B 14	25.0	D 14	25.2					F 14	22.8
A 15	19.4									F 15	23.5
A 16	20.2									F 16	24.5
A 17	19.7										
A 18	20.6										
A 19	16.9										
A 20	20.6										
A v.	19.0		26.6		39.5		36.1		16.3		23.9

The deflection of beam at mid-span was measured by means of a silk thread stretched between two nails set in the wood over each support at one-half the depth of the beam. A mirror and scale placed at the center of the beam permitted the deflection to be read to 0.01 in. The longitudinal or fiber deformation in the extreme fiber was read on the beams of Series C. On two of these the method used was quite similar to that commonly used for determining the neutral axis of reinforced concrete beams, except that the instruments were attached directly to the beam at the extreme fibers. Fig. 5 shows the arrangement of these. In two beams four Johnson extensometers were used and on the remainder only two, one at the top and the other at the bottom of the beam. A gauged length of 36 and of 40 inches was used. Acknowledgment is made to Mr. L. E. Moore for assistance in developing the deformation tests.

An effort was made to take measurements representative of the horizontal shearing slip or detrusion at the ends of the stringers. It was hoped that this method would give some informa-

tion on the action of the horizontal shear and whether there was a shear elastic limit or yield point. The apparatus and methods

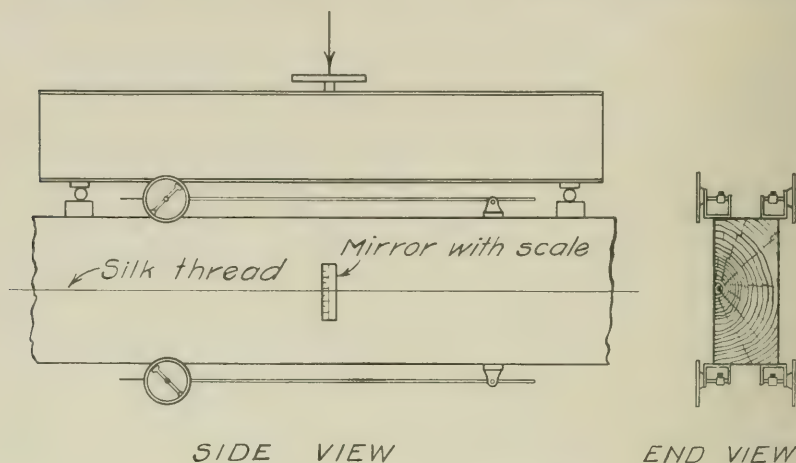


FIG. 5. LOCATION OF INSTRUMENTS.

were tentative and experimental and were not expected to give quantitative results. Two methods were used. In the method used in Series C, the first tried, (see Fig 6(a)) two pointers were fastened by screws to one side of the stringer over a support. On one pointer the screws were 12 in. apart, placed symmetrically with the center or neutral axis of the beam. On the other pointer the two screws were 2 in. apart and symmetrical with the center. Measurements were taken between two points at the upper ends of the pointers. The change in this measurement was due to the horizontal detrusion of the fibers. For the lever arms used, the horizontal movement from equation (5) may be expected to be about two-thirds of the observed reading. In the second method (see Fig. 6(b)) one pointer was fastened at points 12 in. apart as before and the other was secured by two screws in a horizontal line passing through the upper screw of the first pointer. The measurements were taken at the top as before. For the dimension used the horizontal movement would be one-third of the reading. Neither apparatus was fully satisfactory, but the experiments show that a satisfactory instrument may be devised for the purpose and the results found are instructive in several ways, although they are not sufficiently complete and consistent to warrant publication.

10. *Shear Tests.*—In shear tests (see Fig. 7) the shear test block was placed in the testing machine with the grain vertical. A cast-iron plate was put under one-half of the piece and the opposite half at the top was covered with a similar plate. There was a space of perhaps $\frac{1}{4}$ to $\frac{1}{2}$ in. between the vertical lines passing through the edges of these two plates. The tendency of the

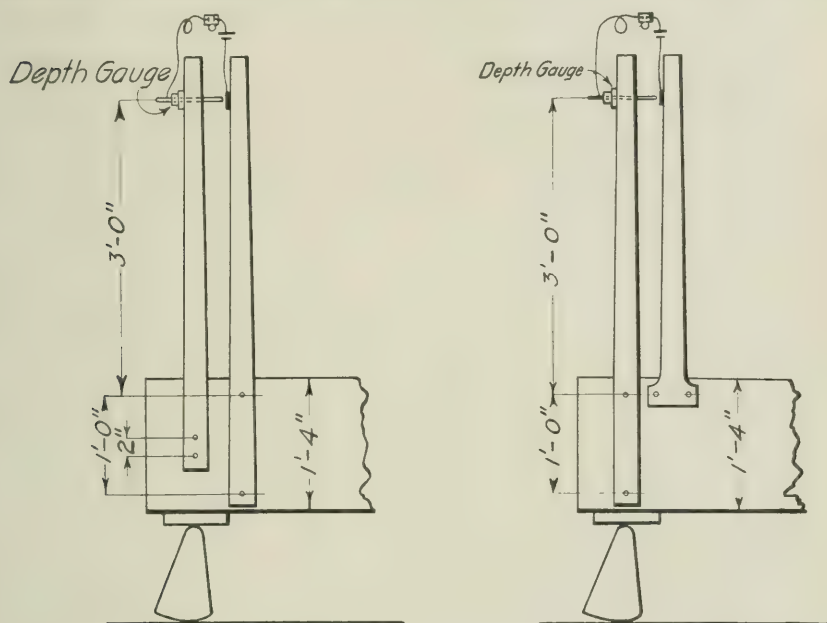


FIG. 6a AND 6b. APPARATUS FOR MEASURING LONGITUDINAL SHEAR MOVEMENT.

block to slip sidewise as the load was applied was counteracted by putting supports between the test piece and the columns of the testing machine. The speed of the machine in these tests was 0.17 in. per minute.

11. *Tests of Small Test Beams.*—The small test beams of the minor and the miscellaneous series were tested generally with a span of 36 in. and the load was applied equally at the one-third points of the span. Care was taken to permit longitudinal movement of the supports as the load was applied. The deflection was measured by a deflectometer with the contact point placed under the center of the beam. A speed of 0.3 in. per minute was used.

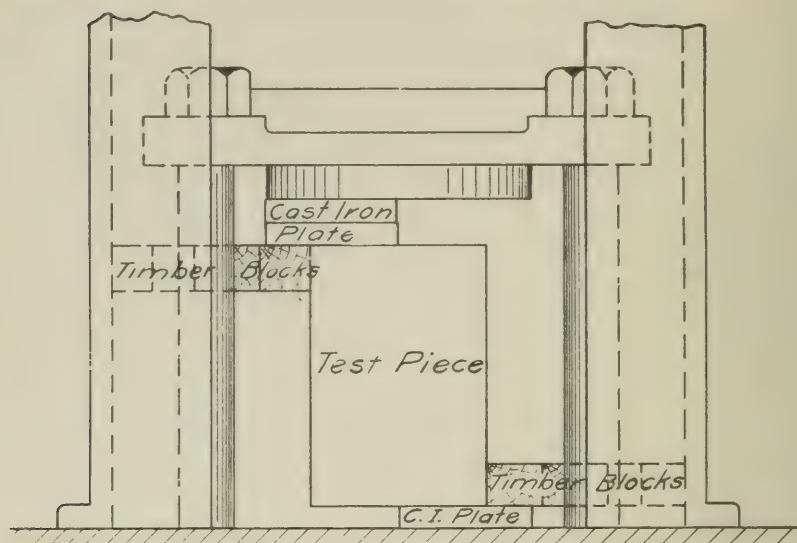


FIG. 7. SHEAR TEST APPARATUS.

III. EXPERIMENTAL DATA AND DISCUSSION.

12. *Stringer Test Data.*—In Tables 5 to 12 are given data for the full-size stringers and their tests as beams in Series A, B, C, D, E, and F. The tables on the left hand pages include a general description of the beams, and the companion tables on the opposite pages give results of the test. The elastic limit was determined from the deflection diagrams by finding the point at which the deflection increases markedly more rapidly than the load. In some cases this involves exercise of judgment. The values so found are somewhat smaller than those which would be obtained by finding the point at which the slope of the curve is 50% greater than the general slope at lower loads. The stress in outer fiber both at the elastic limit and at failure was calculated by using the usual formula (equation (1) p. 7), $M = \frac{1}{6} f b d^2$. The horizontal shearing stress at the neutral axis was calculated by the formula (equation (2) p. 7) $\tau_0 = \frac{3}{2} \frac{V}{b d}$, where V is the total vertical shear at the sec-

tion considered. In the column headed 'Manner of Failure' is given the general way in which failure occurred.

13. *Views and Load-deflection Diagrams.*—The views in Plates 1 to 18 given in the frontispiece are from photographs. They were selected to show representative failures in shear, tension, and compression. In a number of cases the end of the beam before failure and after failure is shown. The difference in appearance in the two ends of the beam is also shown for one beam. The size and appearance of seasoning checks and their relation to the line of shear may be noted. Views of shear blocks are given in Plates 17 and 18. Reference may well be made to the views in following the discussion of the test.

The load-deflection diagrams for Series A, B, C, D, E, F, and N are given in Fig. 11 to 25 at the end of the text. The point selected as the elastic limit is marked on the diagrams.

14. *Phenomena of Tests.*—As the load was progressively applied the beams deflected more and more, and generally failure did not occur until after the elastic limit was passed. In some cases popping sounds were heard. The manner of failures may be classed as (1) tension, (2) compression, (3) horizontal shear. In the tension failure the beam generally failed suddenly by tension in the lower fiber, the crack extending into the beam some distance. In a few cases this tension crack was nearly vertical but there were more instances of cross-grain tension and a few of splintering tension. Beams failing in tension were much affected by the presence of knots and cross grain in the lower portion of the beam. The failures by compression in the upper fiber of the beam were slow and gradual and the load-deflection curves show characteristic features. These failures were generally in poor or brash wood. Seemingly the knots and cross grain had less effect on the compression side than on the tension side. The failures in horizontal shear were very sudden and generally no warning was given, though in a few cases considerable horizontal slip was shown by the instruments and in many cases the increased deflection shown on the deflection curves near the maximum load was probably due to the horizontal shearing movement. After the shear failure and before the head of the testing machine had been moved, the upper portion of the beam at the failed end projected over the lower portion $\frac{1}{4}$ in. or more. The stick continued to carry load, acting as two beams one on top of the other, and when the test

TABLE 5.
DATA OF BEAMS IN SERIES C.

Des.	Nominal Size in. x in. x ft.	Description	Condition
C 1	7 x 16 x 14	Shortleaf pine, untreated (a)	No important knots.
C 2	7 x 16 x 14	Shortleaf pine, untreated (a)	Large seasoning check.
C 3	7 x 16 x 14	Shortleaf pine, untreated (a)	Apparently good stick.
C 4	7 x 16 x 14	Shortleaf pine, untreated (a)	Apparently good stick.
C 5	7 x 16 x 14	Shortleaf pine, creosoted (b)	Apparently good stick.
C 6	7 x 16 x 14	Shortleaf pine, creosoted (b)	Apparently good stick.
C 7	7 x 16 x 14	Shortleaf pine, creosoted (b)	
C 8	7 x 16 x 14	Shortleaf pine, creosoted (b)	
C 9	7 x 16 x 14	Shortleaf pine, creosoted (b)	Slightly cross-grained.
C 10	7 x 16 x 14	Shortleaf pine, creosoted (b)	Cross-grained.
C 11	7 x 16 x 14	Shortleaf pine, creosoted (b)	Knot under south load point.
C 12	7 x 16 x 14	Shortleaf pine, creosoted (b)	Apparently good stick.
C 13	7 x 16 x 14	Loblolly pine, untreated (a)	
C 14	7 x 16 x 14	Loblolly pine, untreated (a)	Four knots under south load.
C 15	7 x 16 x 14	Loblolly pine, untreated (a)	
C 16	7 x 16 x 14	Loblolly pine, untreated (a)	
C 17	7 x 16 x 14	Loblolly pine, creosoted (b)	
C 18	7 x 16 x 14	Loblolly pine, creosoted (b)	
C 19	7 x 16 x 14	Loblolly pine, creosoted (b)	
C 20	7 x 16 x 14	Loblolly pine, creosoted (b)	
C 21	7 x 16 x 14	Loblolly pine, creosoted (b)	Knot under north load.
C 22	7 x 16 x 14	Loblolly pine, creosoted (b)	Knot under south load.
C 23	7 x 16 x 14	Loblolly pine, creosoted (b)	Cross-grained.
C 24	7 x 16 x 14	Loblolly pine, creosoted (b)	

(a) Seasoned 12 months. (b) Seasoned 10 months.

was carried to destruction the second failure was generally by tension and at a load considerably under that causing the shear failure, though in the case of A1, A15 and E1 the maximum load was considerably above that causing the shear failure. The strength of the beams to resist horizontal shear was much affected by seasoning checks and ring shakes.

The following notes of the tests will assist in understanding the manner of failure of the beams. In reading, it will be well to refer to Plates 1 to 16 (frontispiece) and to the load-deflection diagrams at the end of the text.

A 1. Faint cracking at load of 15 000 lb. Loud cracking at 22 500 lb. After failure by horizontal shear at 26 000 lb. in a continuation of the test, the load increased, the stringer acting as two beams, failing by horizontal shear along a second crack at 38 000 lb. See Fig. 11.

A 2. Beyond 40 000 lb. cracking noises were heard. Sudden failure by horizontal shear at north end, resulting in the upper part of the beam projecting over the lower portion $\frac{1}{2}$ in. See Plates 1 and 9.

A 3. Failed suddenly with loud report, by horizontal shear at north end, at 67 500 lb. See Plate 9.

A 4. This beam proved to have a bad ring shake through the middle of the length of the beam, which was the occasion of the tension failure. See Plate 1.

TABLE 6.
TESTS OF BEAMS IN SERIES C.
Stresses are given in lb. per. sq. in.

Des.	Cross Section in. x in.	Elastic Limit		Load at Failure			Manner of Failure
		Load pounds	Fiber Stress	Total pounds	Fiber Stress	Hor. Shearing Stress	
Shortleaf Pine.							
C 1	7.00 x 15.75	Not Reached		43 000	4016	293	Horizontal shear.
C 2	7.00 x 16.12	42 500	3780	45 000	4005	300	Horizontal shear.
C 3	7.00 x 16.38	50 000	4310	54 550	4715	358	Horizontal shear.
C 4	6.75 x 16.00	52 500	4940	72 500	6810	505	Horizontal shear.
C 5	7.00 x 16.00	35 000	3165	40 000	3620	268	Horizontal shear.
C 6	7.00 x 16.00	40 000	3620	47 500	4300	318	Horizontal shear.
C 7	7.25 x 16.12	27 500	2360	42 500	3655	273	Horizontal shear.
C 8	7.00 x 16.00	45 000	4065	47 970	4340	320	Horizontal shear.
C 9	7.00 x 16.00	30 000	2715	33 430	3025	224	Horizontal shear.
C 10	7.12 x 16.25	42 500	3660	55 000	4730	357	Tension
C 11	7.00 x 15.87	27 500	2530	37 000	3405	250	Tension
C 12	7.00 x 16.00	55 000	4970	61 370	5550	410	Horizontal shear.
Loblolly Pine.							
C 13	6.50 x 16.00	40 000	3900	53 000	5160	382	Horizontal shear.
C 14	6.87 x 16.00	42 500	3915	48 860	4500	334	Tension
C 15	7.00 x 16.25	45 000	3940	55 860	4890	368	Horizontal shear.
C 16	7.00 x 16.12	55 000	4900	58 400	5195	388	Horizontal shear.
C 17	7.00 x 16.00	30 000	2710	38 100	3445	255	Horizontal shear.
C 18	7.25 x 15.75	25 000	2155	37 300	3360	245	Horizontal shear.
C 19	7.12 x 16.00	30 000	2670	41 500	3695	273	Horizontal shear.
C 20	7.25 x 16.00	25 000	2180	34 550	3020	224	Horizontal shear.
C 21	7.62 x 15.75	22 500	1930	33 500	2870	209	Tension
C 22	7.50 x 16.50	27 500	2180	40 000	3175	243	Tension
C 23	7.38 x 16.50	25 000	2018	38 240	3085	236	Tension
C 24	7.25 x 16.12	32 500	2795	57 200	4915	368	Horizontal shear.

A 5. Upper portion projected $\frac{3}{8}$ in. after failure by shear.

A 6. Selected to show effect of large knots. At 31 200 lb. loud cracking noise at middle. Failed at 31 700 lb. at large knot near middle. See Plate 1.

A 7. Failed by horizontal shear at north end. Large checks at south end seemed not to affect failure. See Plate 10.

A 8. Sudden failure by shear at 74 000 lb., the shear extending from the south end to the load point and the upper portion projecting $\frac{3}{8}$ in. See Plate 10.

A 9. First failure at 39 750 lb., pure tension. Final failure at 46 850 lb., tension again. See Plate 2 and Fig. 11.

A 10. Knotty and cross-grained in middle third of length. Failed by tension near north load point, then splitting along neutral axis both ways from tension fracture. See Plate 2 and Fig. 11.

A 13. Slight splintering at bottom at 58 600 lb. Further breaking in tension at 60 000 lb. Final failure by horizontal shear at 63 300 lb.

TABLE 7.
DATA OF BEAMS IN SERIES A AND B.

Des.	Nominal Size in. x in. x ft.	Description	Condition
A 1	7 x 16 x 14	Longleaf pine (a)	Large seasoning checks.
A 2	7 x 16 x 14	Longleaf pine (a)	Large checks. Clear stick.
A 3	7 x 16 x 14	Longleaf pine (a)	Good stick.
A 4	7 x 16 x 14	Longleaf pine (a)	Proved to have bad shake.
A 5	7 x 16 x 14	Longleaf pine (a)	Even grain. Good condition.
A 6	7 x 16 x 14	Longleaf pine (a)	Large knots and cross grain.
A 7	7 x 16 x 14	Longleaf pine (a)	Clear and straight-grained.
A 8	7 x 16 x 14	Longleaf pine (a)	Stick clear.
A 9	7 x 14 x 14	Longleaf pine (a)	Bad checks and shakes.
A 10	7 x 14 x 14	Longleaf pine (a)	Cross-grained and knotty.
A 11	7 x 14 x 14	Longleaf pine (a)	Clear and free from knots.
A 12	7 x 14 x 14	Longleaf pine (a)	Clear, straight-grained.
A 13	7 x 14 x 14	Longleaf pine (a)	Fairly clear and straight-grained.
A 14	7 x 14 x 14	Longleaf pine (a)	Knotty and cross-grained.
A 15	7 x 12 x 14	Longleaf pine (b)	Large checks. Sapwood on bottom.
A 16	7 x 12 x 14	Longleaf pine (b)	Clear stick.
A 17	7 x 12 x 14	Longleaf pine (b)	Solid knots on top side.
A 18	7 x 12 x 14	Longleaf pine (b)	Small knots along neutral axis.
A 19	7 x 12 x 14	Longleaf pine (b)	Knot near middle.
A 20	7 x 12 x 14	Longleaf pine (b)	Checks near neutral axis.
B 1	7 x 16 x 14	Longleaf pine (c)	Fairly clear stick.
B 2	7 x 16 x 14	Longleaf pine (c)	Clear and straight.
B 3	7 x 16 x 14	Longleaf pine (c)	Clear stick.
B 4	7 x 16 x 14	Longleaf pine (c)	Grain straight. Clear.
B 5	7 x 16 x 14	Longleaf pine (c)	Grain straight. Clear.
B 6	7 x 16 x 14	Longleaf pine (c)	No knots. Cross-grained.
B 7	7 x 16 x 14	Longleaf pine (c)	Straight. No bad checks.
B 8	7 x 16 x 14	Longleaf pine (c)	Straight. No bad checks.
B 9	7 x 14 x 14	Longleaf pine (c)	Clear, straight grain. Large seasoning check.
B 10	7 x 14 x 14	Longleaf pine (c)	Grain straight. No knots.
B 11	7 x 14 x 14	Longleaf pine (c)	Straight, clear, free of checks.
B 12	7 x 14 x 14	Longleaf pine (c)	Straight, clear, free of checks.
B 13	7 x 14 x 14	Longleaf pine (c)	Straight, clear, free of checks.
B 14	7 x 14 x 14	Longleaf pine (c)	Cross-grained and knotty.

(a) Seasoned 18 months. (b) Seasoned 12 months. (c) Seasoned 4 months.

A 14. At 26 500 lb., failed at knot 2 ft. south of middle. See Plate 2.

A 15. At 22 500 lb. beam sheared at north end, along a wide open seasoning check, upper portion projecting $\frac{5}{16}$ in. Load fell to 20 000 lb. Under further test, projection reached $\frac{1}{2}$ in., and the beam finally failed at 30 000 lb. by tension under the north load. During this time the beam slipped quietly along seasoning check $2\frac{1}{2}$ in. below top on one face and 5 in. below top on the other. This shear gradually approached the middle of the span. After this slip commenced the stringer acted somewhat as two beams. See Fig. 12.

A 16. At 37 500 lb. slight splintering at bottom, and load fell to 34 000 lb., rising then to 39 400 lb. with further tension failure. The load fell to 36 000 lb. and with increased deflection rose to 40 900 lb., the final failure being in horizontal shear at the north end. See Plate 3 and Fig. 12.

A 17. This beam had a number of solid knots $\frac{3}{4}$ in. to $1\frac{1}{4}$ in. across, all at or near the upper surface. The tension side was clear. At 52 900 lb. the beam gave way by tension, the load then dropping slightly, and in about 5 seconds shear failure followed at south end, the upper portion sliding past the lower $\frac{5}{16}$ in. See Plate 11.

A 18. Bad ring checks at south end. Stick strengthened by small knots along neutral axis. See Plates 3 and 12.

TABLE 8.
TESTS OF BEAMS IN SERIES A AND B.
Stresses are given in lb. per sq. in.

Des.	Cross Section in. x in.	Elastic Limit		Load at Failure			Manner of Failure
		Load pounds	Fiber Stress	Total pounds	Fiber Stress	Hor. Shearing Stress	
A 1	6.75 x 15.37	19 500	1960	26 000	2640	188	Horizontal shear.
A 2	6.5 x 16.2	37 500	3060	47 500	4535	340	Horizontal shear.
A 3	7.0 x 16.25	62 500	5480	67 500	5910	445	Horizontal shear.
A 4	7.0 x 16.0	35 000	3150	40 000	3600	267	Tension.
A 5	7.0 x 16.0	53 500	4820	62 500	5640	418	Horizontal shear.
A 6	7.0 x 16.0	28 500	2570	31 700	2860	212	Tension.
A 7	7.0 x 16.0	43 000	3890	47 500	4300	318	Horizontal shear.
A 8	7.0 x 16.0	62 000	5630	74 000	6710	497	Horizontal shear.
A 9	7.0 x 14.0	34 500	4060	46 850	5520	359	Tension.
A 10	7.0 x 14.0	25 000	2940	25 000	2945	191	Tension.
A 11	7.0 x 14.0	48 500	5720	57 500	6820	441	Horizontal shear.
A 12	7.0 x 14.0	48 500	5700	59 050	6950	453	Horizontal shear.
A 13	7.0 x 14.12	47 500	5440	63 300	7260	472	Horizontal shear.
A 14	7.0 x 14.0	25 500	3010	37 300	4400	285	Tension.
A 15	6.87 x 12.0	22 500	3610	22 500	3690	205	Horizontal shear.
A 16	6.6 x 11.75	30 000	5830	39 400	7010	382	Tension.
A 17	7.0 x 12.1	36 500	5800	52 900	8410	471	Tension.*
A 18	6.5 x 11.94	30 000	5200	37 000	6410	356	Horizontal shear.
A 19	7.0 x 12.0	22 000	3540	31 650	5080	282	Tension.
A 20	6.87 x 12.0	32 500	5310	33 400	5460	304	Horizontal shear.
B 1	6.8 x 16.0	45 000	4180	52 500	4890	362	Horizontal shear.
B 2	7.0 x 16.0	56 000	5020	65 100	5880	436	Horizontal shear.
B 3	6.92 x 15.95	55 000	5080	68 000	6260	462	Horizontal shear.
B 4	7.20 x 16.32	61 000	5160	64 300	5430	410	Horizontal shear.
B 5	7.20 x 16.62	56 000	4560	75 600	6160	474	Horizontal shear.
B 6	6.87 x 16.06	56 000	5110	66 700	6080	454	Horizontal shear.
B 7	7.0 x 16.0	46 000	4150	58 350	5270	390	Horizontal shear.
B 8	6.9 x 15.95	40 000	3720	58 900	5430	401	Horizontal shear.
B 9	7.1 x 14.1	30 000	3440	31 600	3620	237	Horizontal shear.
B 10	7.12 x 14.06	41 000	4720	56 750	6540	425	Horizontal shear.
B 11	7.25 x 14.05	35 000	3960	36 900	4180	272	Horizontal shear.
B 12	7.05 x 14.0	41 500	4860	50 900	5970	387	Horizontal shear.
B 13	6.87 x 14.0	33 000	3970	46 300	5570	362	Horizontal shear.
B 14	6.95 x 14.0	33 000	3560	44 600	5300	344	Tension.

* Followed quickly by horizontal shear.

A 19. Cracking sound at 22 000 lb., seemingly something giving way. Increased deflection above this load is shown on deflection diagram. Tension failure. Brash wood. See Plate 3.

A 20. Sheared suddenly at north end, plainly due to large seasoning checks. See Plate 12.

B 1. Considerable sapwood at top and bottom. Failed by horizontal shear along neutral axis. Shear in tortuous line. See Plate 13.

B 3. A load of 65 000 lb. was applied, giving a deflection of 1.36 in. After release of load a set of 0.06 in. was observed. At the second application of 65 000 lb. the deflection was 1.37 in. Failed by shear at north end at 68 000 lb.

B 9. Large, deep seasoning checks nearly continuous. Free from knots, failed in horizontal shear along seasoning check.

B 10. No seasoning checks except at extreme end. Failed by horizontal shear at high load.

TABLE 9.
DATA OF BEAMS IN SERIES D.

Des.	Nominal Size in. x in. x ft.	Description	Condition
D 1	7 x 16 x 14	Loblolly pine, untreated (a)	Large knot outside load point.
D 2	7 x 16 x 14	Loblolly pine, untreated (a)	Knot near middle.
D 3	7 x 16 x 14	Loblolly pine, untreated (a)	Several knots.
D 4	7 x 14 x 14	Loblolly pine, untreated (a)	Straight-grained and clear.
D 5	7 x 14 x 14	Loblolly pine, untreated (a)	Very knotty; no checks.
D 6	7 x 14 x 14	Loblolly pine, untreated (a)	Very knotty; no checks.
D 7	7 x 14 x 14	Loblolly pine, untreated (a)	Few knots.
D 8	7 x 14 x 14	Loblolly pine, untreated (a)	Slight cross-grain and checks.
D 9	7 x 14 x 14	Loblolly pine, untreated (a)	Straight-grained, 1 large check.
D 10	7 x 16 x 14	Loblolly pine, untreated (a)	Straight-grained, 1 large check.
D 11	7 x 16 x 14	Loblolly pine, untreated (a)	Knots on neutral axis.
D 12	7 x 16 x 14	Loblolly pine, untreated (a)	Straight-grained, fairly clear.
D 13	7 x 16 x 14	Loblolly pine, untreated (a)	Straight-grained.
D 14	7 x 16 x 14	Loblolly pine, untreated (a)	Cross-grained. A few knots and checks.
D 15	7 x 16 x 14	Loblolly pine, creosoted (b)	Large knots along neutral axis.
D 16	7 x 16 x 14	Loblolly pine, creosoted (b)	Large knots. Cross grain.
D 17	7 x 14 x 14	Loblolly pine, creosoted (b)	Cross grain.
D 18	7 x 14 x 14	Loblolly pine, creosoted (b)	Brash wood.
D 19	7 x 14 x 14	Loblolly pine, creosoted (b)	Good condition.
D 20	7 x 16 x 14	Loblolly pine, creosoted (b)	Knots along neutral axis.
D 21	7 x 14 x 14	Loblolly pine, creosoted (b)	Rather knotty at one end.
D 22	7 x 16 x 14	Loblolly pine, creosoted (b)	Straight-grained and clear.
D 23	7 x 16 x 14	Loblolly pine, creosoted (b)	Straight-grained and clear.
D 24	7 x 16 x 14	Loblolly pine, creosoted (b)	A few knots.
D 25	7 x 14 x 14	Loblolly pine, creosoted (b)	Several large knots.
D 26	7 x 14 x 14	Loblolly pine, creosoted (b)	Fairly clear and straight-grained.

(a) Seasoned 6 months. (b) Seasoned 2 months.

B 11. Seasoning checks, but not very marked or deep. Failed by horizontal shear along seasoning check.

B 13. 2 in. sapwood at top. Few seasoning checks. Free from knots. Bearing plate at north load induced crushing in upper fiber near it at a load 1000 lb. below maximum, and slight splintering tension failure occurred at bottom below this point, but main failure was by horizontal shear at the south end at the maximum load. The compression failure finally extended from the top fiber nearly to the neutral axis.

B 14. Failed by tension below a large knot which was on the compression side.

C 2. Failure by horizontal shear along seasoning crack 2 in. above neutral axis.

C 3. Failure by horizontal shear along neutral axis.

C 4. After failure by horizontal shear along neutral axis, upper portion projected $\frac{3}{8}$ in. Highest shearing strength in this series.

C 5. Failed by horizontal shear under deflection of 14 in. Load fell off. Upon increasing the deflection, it rose to 33 890 lb. and failed in tension under a deflection of 2 in.

C 7. Bearing plate under one load crushed unevenly into wood at 40 000 lb. Load released, plate adjusted, and load applied to failure.

C 8. Load of 35 000 lb. was released, bearing plate at support adjusted and load applied to failure (48 000 lb.). After failure by horizontal shear, load was further applied and failure in tension occurred at 39 600 lb. under a deflection $2\frac{1}{2}$ in. more than at shear failure.

C 9. Failed by shearing at south end at 33 430 lb. under deflection of 1.09 in. Load dropped to 32 000 lb., then rose to 35 000 lb. under a deflection

TABLE 10.

TESTS OF BEAMS IN SERIES D.

Stresses are given in lb. per sq. in.

Des.	Cross Section in. x in.	Elastic Limit		Load at Failure			Manner of Failure
		Load pounds	Fiber Stress	Total pounds	Fiber Stress	Hor. Shearing Stress	
D 1	6.87 x 16.0	41 500	3820	56 000	5150	381	Horizontal shear.
D 2	7.25 x 16.25	33 000	2790	48 700	4120	310	Tension.
D 3	7.13 x 16.8	27 000	2180	41 800	3360	262	Tension.
D 4	7.1 x 14.0	32 000	3730	49 100	5740	371	Horizontal shear.
D 5	7.2 x 14.0	17 000	1950	22 000	2530	164	Tension.
D 6	6.81 x 14.06	18 000	2160	29 300	3520	229	Tension.
D 7	7.05 x 13.72	30 000	3660	42 000	5130	325	Tension.
D 8	6.95 x 14.10	22 000	2620	29 350	3490	226	Tension.
D 9	6.55 x 14.05	27 000	3370	31 000	3880	253	Horizontal shear.
D 10	6.9 x 16.20	33 000	2950	42 000	3760	282	Horizontal shear.
D 11	7.25 x 16.0	32 500	2830	50 500	4410	325	Tension.
D 12	7.1 x 16.15	33 500	2940	46 800	4100	305	Horizontal shear.
D 13	7.25 x 16.45	37 500	3100	52 200	4310	328	Horizontal shear.
D 14	6.45 x 16.07	24 000	3320	38 700	3770	281	Horizontal shear.
D 15	7.1 x 16.25	42 500	3680	54 700	4740	356	Tension.
D 16	7.37 x 16.37	18 500	1460	32 500	2660	202	Tension.
D 17	7.0 x 14.0	30 000	3530	42 700	5030	327	Tension.
D 18	6.87 x 14.0	30 000	3600	41 700	5000	325	Tension.
D 19	7.0 x 14.0	34 000	4020	51 500	6080	394	Tension.
D 20	7.0 x 15.5	45 000	4330	46 400	4460	320	Horizontal shear.
D 21	7.75 x 14.0	40 000	4280	56 400	6020	391	Crush. and hor. shear.
D 22	7.1 x 16.5	42 500	3570	65 500	5500	420	Crushing and tension.
D 23	7.0 x 16.0	50 000	4510	56 500	5100	378	Crush. and hor. shear.
D 24	7.5 x 16.25	51 000	4180	55 475	4550	341	Crushing.
D 25	7.5 x 14.25	23 500	2500	31 100	3300	218	Tension.
D 26	7.0 x 13.75	27 500	3380	37 000	4540	289	Tension.

of 3.08 in., when the shearing fracture extended the entire length of the beam. Very low shearing strength.

C10. Failed by tension at center due to cross grain. Contributory crushing under north support. Loading released. On second application, load reached 50 200 lb. under 3 in. additional deflection, when further failure in tension occurred.

C11. Failure by tension due to knot under south load point.

C13. Failed at one end by horizontal shear along neutral axis.

C14. Failure by tension under south load point. Four knots near break.

C15. Marked change in deflection curve evidently due to horizontal shearing action.

C16. Slight splintering at bottom when horizontal shear failure occurred.

C17. After horizontal shear failure at south end at 38 100 lb. load dropped, and on further deflection rose to 26 200 lb., the beam then failing by tension under south load point.

C18. Crushing (bearing) under bearing plates at load points and over supports at the load which gave horizontal shear failure.

C19. Crushing (bearing) over bearing plate at north support showed at 27 500 lb. At 40 000 lb. crushing was so great that load was released and support adjusted. Failure by horizontal shear at 41 500 lb.

TABLE 11.

DATA OF BEAMS IN SERIES E AND F.

Des.	Nominal Size in. x in. x ft.	Description	Condition
E 1	7 x 16 x 15	Old Douglas fir (a)	Straight-grained.
E 2	7 x 16 x 15	Old Douglas fir (a)	Straight-grained.
E 3	7 x 16 x 15	Old Douglas fir (a)	Straight-grained.
E 4	7 x 16 x 15	Old Douglas fir (a)	
E 5	7 x 16 x 15	Old Douglas fir (a)	Straight-grained.
E 6	7 x 16 x 15	Old Douglas fir (a)	Small unimportant knots.
E 7	7 x 16 x 15	Old Douglas fir (a)	Straight-grained. Few knots.
E 8	7 x 16 x 15	Old Douglas fir (a)	Knotty and cross-grained.
E 9	7 x 16 x 15	Old Douglas fir (a)	Knotty and rather crooked grain.
E 10	7 x 16 x 15	Old Douglas fir (a)	Crooked grain, one large knot.
E 11	7 x 16 x 15	Old Douglas fir (a)	Fairly straight-grained.
E 12	7 x 16 x 15	Old Douglas fir (a)	Numerous knots. Crooked grain.
F 1	8 x 16 x 15	New Douglas fir (b)	Fairly clear stick.
F 2	8 x 16 x 15	New Douglas fir (b)	Several large solid knots.
F 3	8 x 16 x 15	New Douglas fir (b)	Large seasoning checks.
F 4	8 x 16 x 15	New Douglas fir (b)	Large seasoning checks.
F 5	8 x 16 x 15	New Douglas fir (b)	Prominent seasoning checks.
F 6	8 x 16 x 15	New Douglas fir (b)	Deep seasoning checks.
F 7	8 x 16 x 15	New Douglas fir (b)	Very knotty. Cross-grained.
F 8	8 x 11 x 15	New Douglas fir (b)	Very knotty. Cross-grained.
F 9	8 x 16 x 15	New Douglas fir (b)	Straight-grained. Large checks.
F 10	8 x 16 x 15	New Douglas fir (b)	Cross-grained. Prominent check.
F 11	8 x 16 x 15	New Douglas fir (b)	Slightly cross grained. A few small knots.
F 12	8 x 16 x 15	New Douglas fir (b)	Fairly straight-grained. Small knots.
F 13	8 x 16 x 15	New Douglas fir (b)	Fairly straight-grained. Small knots.
F 14	8 x 16 x 15	New Douglas fir (b)	Straight-grained.
F 15	8 x 16 x 15	New Douglas fir (b)	Knotty and cross-grained.
F 16	8 x 16 x 15	New Douglas fir (b)	Numerous small knots.

(a) Seasoned 11 years. (b) Partly seasoned.

C20. At 26 600 lb. tension break in lower fiber near knot occurred. Effect of this is shown in deflection curve. Failure by horizontal shear at 34 550 lb. See Fig. 15.

C21. Failure by tension at knot under north load. Contributory crushing under bearing plate at same load.

C22. Failure by tension under south load near knot.

C23. Failure by tension. Cross-grained.

C24. Failure by horizontal shear, with splintering at bottom.

D1. Large amount of sapwood, 3 in. at bottom. Three rings to 1 inch. Marked seasoning checks at ends and sides. Large deflection. Failure by horizontal shear. Shearing fracture influenced by crooked grain around knot. See Plate 4.

D2. Four inches of sapwood at top, 3 in. at bottom. Free from seasoning checks except at ends. Large knot near middle at bottom. Loud cracking noise at 47 000 lb. Failed by tension at knot near middle, followed at once by horizontal shear. See Plates 4 and 14.

D3. Large amount of sapwood, 4 in. at top and at bottom. Coarse wood. Large knot near top on east side near middle of length. Beam tilted on loading. Load released, beam straightened up and load applied. Failed in tension by splintering along the bottom. See Plate 14.

D4. Large amount of sapwood, 4 in. at top and 3 in. at bottom. Straight-grained. Fairly free from seasoning cracks and knots. Failed by shear with tension break at same time under south load. See Plate 14.

D5. Heart at west face. Wood coarse and brash. East face sapwood, quite soft. Large knot (5 in.) under upper bearing plate and large knot

TABLE 12.

TESTS OF BEAMS IN SERIES E AND F.

Stresses are given in lb. per sq. in.

Des.	Cross Section in. x in.	Elastic Limit		Load at Failure			Manner of Failure
		Load pounds	Fiber Stress	Total pounds	Fiber Stress	Hor. Shearing Stress	
E 1	6.6 x 15.45	27 500	3050	30 000	3320	221	Horizontal shear.
E 2	6.7 x 15.55	50 000	5360	51 400	5510	369	Horizontal shear.
E 3	6.81 x 15.31	45 000	4970	47 700	5270	378	Horizontal shear.
E 4	7.0 x 15.75	32 500	3260	37 500	3770	256	Horizontal shear.
E 5	6.75 x 15.63	30 000	3160	32 500	3430	231	Horizontal shear.
E 6	6.75 x 15.5	32 500	3490	33 600	3610	241	Horizontal shear.
E 7	6.63 x 15.88	28 500	2960	37 500	3910	268	Horizontal shear.
E 8	7.0 x 15.88	42 000	4120	42 000	4120	282	Tension.
E 9	6.75 x 15.5	47 500	5090	53 500	5730	383	Horizontal shear.
E 10	6.75 x 15.88	22 500	2360	32 500	3260	223	Tension.
E 11	6.75 x 15.75	45 000	4660	47 800	4980	337	Horizontal shear.
E 12	7.0 x 16.0	35 000	3500	45 000	4500	301	Horizontal shear.
F 1	8.0 x 15.85	43 000	3730	49 100	4260	291	Horizontal shear.
F 2	8.0 x 15.95	40 000	3420	46 600	3990	275	Horizontal shear.
F 3	8.0 x 15.87	45 500	3940	48 850	4220	289	Horizontal shear.
F 4	7.9 x 15.80	39 500	3410	47 000	4150	282	Horizontal shear.
F 5	8.0 x 15.77	57 000	4980	58 000	5070	345	Horizontal shear.
F 6	7.9 x 15.90	56 000	4890	57 000	4970	340	Horizontal shear.
F 7	7.7 x 15.55	33 500	2920	38 200	3690	239	Tension.
F 8	7.7 x 15.60	27 500	2550	35 000	3250	219	Tension.
F 9	8.0 x 15.75	52 500	4700	67 500	6040	401	Horizontal shear.
F 10	8.0 x 16.0	37 500	3180	42 500	3610	332	Tension.
F 11	8.0 x 15.63	46 500	4080	51 250	4510	304	Horizontal shear.
F 12	8.0 x 16.0	50 000	4250	62 500	5310	366	Horizontal shear.
F 13	8.0 x 16.13	48 500	4020	52 500	4340	302	Horizontal shear.
F 14	8.0 x 15.88	50 000	4280	57 500	4710	322	Tension.
F 15	8.0 x 16.13	52 500	4370	65 000	5400	376	Horizontal shear.
F 16	8.13 x 15.88	54 000	4560	61 350	5180	355	Tension.

(4 in.) near bottom and under north load. Not merchantable stick. Failure by tension under north load.

D6. Three inches of sapwood at top and bottom. Large knots near neutral axis. Failed by tension near large knot. Coarse dark-colored sapwood at point of failure. Little bond between rings. Ring shake developed in middle third.

D7. Little sapwood. Straight-grained. The prominent seasoning cracks were staggered towards the ends and seemed not to affect the strength. Failed in tension at standard knot in middle of bottom face.

D8. Very coarse wood, free from seasoning checks, knots under each load point. Failed by tension, the fracture running from the bottom under one load point to the top under the other.

D9. Good grain for loblolly. Very marked seasoning checks on both faces through north third of length. Failed by horizontal shear at north end along these prominent seasoning checks.

D10. Straight grained. Coarse wood. Little sapwood. Large knot at neutral axis at south end. Failed by horizontal shear at north end along deep seasoning check.

D11. Many knots along neutral axis. Large amount of sapwood, 4 in. at bottom and 2 in. at top. Marked seasoning checks on west face, but staggered. Numerous knots along neutral axis. Failed by tension; probably due to sapwood. See Plate 4.

D 12. Free from seasoning checks. Knots not at important places. Failed in tension under south load. Fair break. Timber seemed soft and brash.

D 13. Free from seasoning checks. Brashy sapwood on under side. Several small spike knots. Failure by tension in sapwood.

D 14. Failed at south end by shear along seasoning checks, which were near neutral axis on west side but on east side ran toward bottom at south end.

D 15. Failed by tension at center. Load fell off to 42 000 lb., when crushing began above the tension failure.

D 16. Five knots on east side $1\frac{1}{2}$ to 3 in. On west side one knot 2 x 9 in. and one $1\frac{1}{2}$ x 8 in., both extending to bottom of beam. Not merchantable stick. Abnormally large deflection. Failure by tension near large knot.

D 17. Three large knots. Failed by tension at knot under south load.

D 18. The wood seemed brittle and of inferior quality. Splintering at bottom at load of 37 500 lb. Failure was sudden and complete, the stick being badly shattered and not capable of carrying any load. See Plate 5.

D 19. At 46 500 lb. slight splintering at bottom. At 51 500 lb. popping noise at middle. Load gradually dropped to 49 100 lb. Then beam gave way, there being three distinct loud pops about $\frac{1}{2}$ second apart as the beam failed by tension at the middle.

D 20. Slight splintering on under side near maximum load. Final failure by shear near north end. When failure occurred, the north support was thrown out to the north against a pile of beams, the beam itself shot out south 5 ft. Creosote had been squeezed out of the wood over the bearing plates, and slipping thus more easily occurred.

D 21. Several large knots in north half, which apparently did not affect the strength at the load reached. Crushing began under north load at 56 000 lb., the load went up to 56 400 lb., then dropped to 56 200 lb., when failure by crushing and horizontal shear occurred simultaneously. See Plates 5 and 14.

D 22. At 59 750 lb. slight splintering on bottom. At 63 500 lb. piece splintered off below north load to north end. Bearing plate crushing into wood. At 64 500 lb. crushing apparent north of north load. Largest load 65 500 lb., when stick reached bed of machine, still carrying the load. Failure combination of tension and compression. See Fig. 17.

D 23. At 51 650 lb. crushing became apparent at north load and deflections beyond this were much increased. Failure at 56 500 lb. by crushing and horizontal shear at north end simultaneously.

D 24. This beam is a good illustration of the action of several of the creosoted loblolly stringers. Beyond 52 500 lb. the deflection increased very rapidly, and the stick seemed to act like water-soaked or steamed wood, bending like a very soft wood. Although slight splintering occurred on the bottom at the north end, failure was due to crushing which was quite apparent at both load points at 52 700 lb. (evidently occasioned by the bearing blocks crushing into the wood), and failure occurred at 56 300 lb.

D 25. Failed by tension at knot near south load. Beam lacked stiffness. See Plate 5.

D 26. Tension failure under north load.

E 1. At 29 800 lb. loud cracking occurred and load fell off to 20 000 lb.—evidently a shear failure. Load picked up and deflections increased rapidly thereafter, the stick acting as two beams. At 40 000 lb. the upper portion of south end was projecting $\frac{1}{2}$ in. The maximum load carried was 43 800 lb. See Plates 6 and 15 and Fig. 18.

E2. Failure along seasoning crack by horizontal shear at 51 400 lb. with loud report. Load dropped to 24 000 lb.; stiff beam.

E3. The great increase in deflection after load of 44 800 lb. was evidently due to incipient shear failure and not to fiber elastic limit having been reached. Sheared at south end (sawed end) at 47 700 lb. along a line 4 in. below top. Load dropped to 30 400 lb. rose to 40 000 lb. after a further deflection of 0.62 in., when it failed by horizontal shear at the same end along a second line 3 in. from bottom.

E4. Failed by horizontal shear at north end. This end was the sawed end and was originally next to the end which failed in E3.

E5. Failed by horizontal shear at sawed end 7 in. below top at 32 500 lb. Load dropped to 15 750 lb. Load rose to 34 300 lb. when the beam sheared again at same end, this time 4 in. above bottom. The load then dropped to 22 700 lb. See Plate 15.

E6. Failure by horizontal shear at sawed end 7 in. below top at 33 600 lb. Load dropped to 20 000 lb. and finally rose to 29 100 lb. when it sheared again at the same end, this time 5 in. above bottom. Load dropped to 14 000 lb.

E7. Failed by horizontal shear at unsawed end at mid-depth at 37 500 lb. Load dropped to 22 500 lb. With the deflection increased from 0.8 in. to over 3 in., the load rose to a maximum of 47 300 lb., when splintering at the bottom occurred. See Plate 15.

E8. Failed by splintering tension at 42 000 lb. Strength affected by cross-grain.

E9. Failed at sawed end by horizontal shear along inclined line at 53 500 lb. Load dropped to 28 000 lb. and with 1.5 in. additional deflection rose to 41 300 lb. The view shows final break. See Plate 6.

E10. Large knot at center of bottom. At 23 100 lb. splitting began on tension side, and deflection increased rapidly after this. Failed by tension at 32 500 lb. See Plate 6 and Fig. 18.

E11. Failed by horizontal shear at sawed end at 47 800 lb. Load fell to 27 600 lb. With increased deflection load rose to 49 900 lb., when the beam failed by tension at the middle. See Plate 15.

E12. At 36 700 lb., 37 900 lb., and 38 200 lb., there were slight splinterings, accompanied each time by slight drop in load. Failed at unsawed end by horizontal shear at 45 000 lb. Load fell to 26 950 lb.

F1. Failed at sawed end by horizontal shear at 49 100 lb. Failure cracks inclined. Tension splintering also occurred under north load. See Plate 16.

F2. Very knotty stick. Large knot at bottom under north load. Another knot one foot away. At 44 700 lb. seemingly giving way in tension at middle, with loud report. Increased deflection afterward. Failure by horizontal shear along neutral axis at 46 600 lb. although at 44 700 lb. a loud report and seeming failure at bottom indicated an approaching tension failure. See Plate 7.

F3. Failure by horizontal shear at 48 850 lb. Load dropped to 25 000 lb. See Plate 7.

F4. Failure at unsawed end by horizontal shear at 47 000 lb. Loud report. See Plate 7.

F5. Failure at unsawed end by horizontal shear along prominent seasoning cracks opposite heart at 55 000 lb. Line of shear across middle 4 in. followed around annual ring.

F6. Somewhat cross-grained. Several large knots near neutral axis. One 2-in. knot in middle near top. Deep seasoning checks opposite heart. Failed at unsawed end by horizontal shear at 57 000 lb. See Plate 16.

F 7. Tension failure. The grain around a knot just below the middle was quite irregular. A shake also showed itself along the fracture. See Plate 8.

F 8. Considerable sapwood. Cracking noise at 27 500 lb. Loud cracking at 32 500 lb. Tension failure under south load point, followed immediately by horizontal shear at the north (sawed) end.

F 9. Heart at one face. Loaded twice—first time to 61 300 lb. Deflection set on release of load, 0.13 in. At second application of this load deflection was 0.25 in. greater than on first loading. Failed at unsawed end by horizontal shear at 67 500 lb.

F 10. Heart at one face. Cross-grained. Cracking noises at each application of load from 20 000 lb. on. Tension failure at 42 500 lb. Cross-grained failure. See Plate 8.

F 11. Cracking noises in middle at several loads from 12 500 lb. on. Failed at sawed end by horizontal shear at 51 250 lb. See Plate 16.

F 12. Failed at unsawed end by horizontal shear.

F 13. Failed at unsawed end by horizontal shear through heart.

F 14. Failed by tension under south load point, followed immediately by horizontal shear at the unsawed end. See Plates 8 and 16.

F 15. Failed at unsawed end by horizontal shear, followed by slight tension failure on west side in middle third.

F 16. Cracking noises on application of loads from 17 500 lb. on. Failure by tension, the splinter starting from large knot under south load point.

15. *Shear Test Data.*—In Table 13, are given data of the shearing tests of blocks cut from the full-size stringers of Series A, B, D, E, and F. In pieces from creosoted sticks the failure was gradual, something like a yield point being noticed, and there was a considerable longitudinal movement before final failure. In the untreated pieces the failures were generally quite sudden. In the few pieces in which small knots were present along the line of the shearing surface, greater resistance to shear was noted. Generally speaking, failure was more frequently along seasoning checks or else the failure line coincided with such checks for some distance. Plates 17 and 18 give views of shear test pieces after test and also show the position of seasoning checks.

16. *Small Beam Test Data.*—In Table 13 data of the cross-bending tests of small beam test pieces taken from stringers in Series A, B, D, E, and F are given. The failures were generally by tension or compression and at loads well above the elastic limit of the material.

17. *General Results of Tests.*—Table 14 gives a summary of the results of the tests of stringers and of the minor test pieces taken from them. Care should be exercised to take into consideration the differences in conditions before drawing conclusions, as, for example, the obvious defects of some of the sticks, the

TABLE 13.

TESTS OF MINOR TEST PIECES.

Stresses are given in lb. per sq. in.

Small Beams, 3 x 3 x 40 inches					Shear Blocks Approximately 7 x 12 in.	
Des.	Elastic Limit	Fiber Stress	Hor. Shear'g Stress	Manner of Failure	Design- ation	Shearing Stress
A 1a	10 640	12 000	750	Tension	A 1y	644
A 1b	8 780	10 450	654	Tension	A 1z	497
A 1c	6 675	10 000	625	Tension		
A 1d	6 680	10 000	625	Tension		
A 2a	9 525	13 800	860	Tension	A 2y	324
A 2b	8 700	8 700	533	Tension	A 2z	292
A 2c	6 670	10 000	625	Tension		
A 2d	6 675	10 000	625	Tension		
A 3a	6 950	9 980	622	Tension	A 3y	785
A 3b	7 990	10 350	647	Tension	A 3z	454
A 3c	6 470	6 470	396	Tension		
A 3d	5 430	8 760	475	Tension		
A 4a	8 270	10 050	629	Tension	A 4y	629
A 4b	8 000	8 670	541	Tension	A 4z	359
A 4c	4 170	4 580	292	Tension		
A 4d	4 260	4 650	292	Tension		
A 5a	5 330	9 730	608	Tension	A 5y	521
A 5b	6 810	10 900	682	Tension	A 5z	336
A 5c	5 360	5 360	333	Tension		
A 5d	6 650	7 520	472	Tension		
A 6a	5 850	6 860	430	Tension	A 6y	609
A 6b	10 000	10 950	683	Tension	A 6z	680
A 6c	6 000	8 400	524	Tension		
A 6d	6 660	8 060	504	Tension		
A 7a	8 520	10 850	680	Tension		
A 7b	6 940	10 600	664	Tension		
A 7c	8 000	10 000	625	Tension		
A 7d	6 270	8 800	550	Tension		
A 8a	6 670	8 800	550	Tension	A 8y	710
A 8b	4 270	4 400	275	Tension	A 8z	482
A 8c	6 200	6 200	388	Tension		
A 8d	7 480	8 720	583	Tension		
A 9a	2 130	3 510	219	Hor. shear	A 9y	428
A 9b	6 390	7 560	463	Tension	A 9z	514
A 9c	5 600	10 000	625	Hor. shear		
A 9d	5 875	7 840	491	Tension		
A 10a	6 800	9 740	608	Tension	A10y	134
A 10b	4 000	4 000	250	Tension	A10z	35
A 10c	6 800	8 540	533	Tension		
A 10d	6 670	8 860	545	Tension		
A 11a	6 670	8 200	513	Tension	A11y	357
A 11b	6 820	10 900	613	Tension	A11z	398
A 11c	6 280	9 810	680	Tension		
A 11d	7 170	10 300	647	Tension		
A 12a	8 000	10 000	625	Tension	A12y	444
A 12b	5 330	5 330	333	Hor. shear	A12z	384
A 12c	5 570	8 600	540	Tension		
A 12d	8 140	9 300	582	Tension		

TABLE 13. (Continued)
TESTS OF MINOR TEST PIECES.
Stresses are given in lb. per sq. in.

Small Beams, 3 x 3 x 40 inches					Shear Blocks Approximately 7 x 12 in.	
Des.	Elastic Limit	Fiber Stress	Hor. Shear'g Stress	Manner of Failure	Designation	Shearing Stress
A 13a	6 140	8 940	558	Tension	A13y	530
A 13b	6 675	9 940	621	Tension	A13z	783
A 13c	7 210	10 400	650	Tension		
A 13d	10 000	11 650	728	Tension		
A 14a	7 650	11 750	720	Tension	A14y	316
A 14b	5 980	7 050	442	Tension	A14z	410
A 14c	4 800	5 330	333	Hor. shear		
A 14d	6 000	8 720	547	Hor. shear		
A 15a	8 000	8 320	522	Hor. shear		
A 15b	10 150	13 500	842	Tension		
A 15c	6 675	10 650	668	Tension		
A 15d	9 340	9 340	583	Tension		
A 16a	6 680	10 050	620	Tension	A16y	506
A 16b	6 660	10 650	667	Tension	A16z	594
A 16c	4 000	5 730	358	Tension		
A 16d	7 330	9 100	569	Tension		
A 17a	7 930	11 500	719	Tension		
A 17b	8 500	10 100	619	Tension		
A 17c	8 670	9 860	617	Tension		
A 17d	8 660	10 400	650	Hor. shear		
A 18a	7 890	7 890	503	Hor. shear	A18y	548
A 18b	7 450	9 050	567	Hor. shear	A18z	525
A 18c	5 320	9 450	592	Tension		
A 18d	6 680	10 050	629	Tension		
A 19a	4 670	6 000	375	Tension	A19y	456
A 19b	5 450	6 370	397	Tension	A19z	392
A 19c	2 670	3 270	204	Tension		
A 19d	4 410	4 670	232	Tension		
A 20a	8 000	10 000	625	Crushing	A20y	290
A 20b	8 000	10 150	635	Tension		
A 20c	8 650	8 650	542	Tension		
A 20d	9 350	9 350	583	Tension		
Av.	6 835	8 810	550			466
B 1b	5 380	7 000	432	Crushing	B 1y	488
B 1c	5 140	7 320	474	Crushing	B 1z	546
B 2a	7 850	8 900	561	Tension	B 2y	353
B 2b	7 280	9 850	612	Crushing	B 2z	515
B 2c	5 940	6 980	436	Crushing		
B 2d	5 300	7 550	472	Crushing		
B 3a	6 340	8 180	513	Crushing	B 3y	272
B 3b	5 860	6 900	434	Crushing	B 3z	585
B 3c	5 950	8 600	541	Tension		
B 3d	6 460	9 000	560	Tension		
B 4a	7 725	11 300	702	Crushing	B 4y	221
B 4b	7 330	10 900	668	Crushing	B 4z	423
B 4c	6 550	10 900	670	Tension		
B 5a	9 880	12 300	733	Crushing	B 5y	378
B 5b	9 080	11 800	716	Crushing	B 5z	524
B 5c	7 200	9 100	322	Tension		
B 5d	7 180	9 600	560	Crushing		

TABLE 13. (Continued)

TESTS OF MINOR TEST PIECES
Stresses are given in lb. per sq. in.

Small Beams, 3 x 3 x 40 inches					Shear Blocks Approximately 7 x 12 in.	
Des.	Elastic Limit	Fiber Stress	Hor. Shear'g Stress	Manner of Failure	Design- ation	Shearing Stress
B 6a	4 920	6 620	416	Crushing	B 6y	366
B 6b	5 430	7 640	473	Crushing	B 6z	505
B 6c	6 720	8 850	552	Tension		
B 6d	7 000	9 440	591	Crushing		
B 7a	5 650	7 630	476	Crushing	B 7y	362
B 7b	5 430	7 130	445	Crushing	B 7z	376
B 7c	5 220	7 400	460	Crushing		
B 7d	4 750	7 060	437	Tension		
B 8a	5 300	6 100	380	Crushing	B 8y	386
B 8b	5 520	6 500	408	Crushing	B 8z	465
B 8c	6 440	8 220	508	Tension		
B 8d	6 240	9 340	583	Tension		
B 9a	7 250	9 450	578	Crushing	B 9y	254
B 9b	6 540	7 410	619	Crushing	B 9z	375
B 9c	5 960	9 700	600	Tension		
B 9d	6 490	10 000	618	Tension		
B 10a	6 475	8 250	508	Crushing	B 10y	276
B 10b	5 590	7 450	468	Crushing	B 10z	341
B 10c	6 150	9 850	609	Tension		
B 10d	5 960	9 000	563	Tension		
B 11a	5 010	6 850	430	Crushing	B 11y	381
B 11b	5 150	6 800	427	Crushing	B 11z	392
B 11c	5 670	8 800	549	Tension		
B 11d	5 460	8 530	532	Tension		
B 12a	6 190	8 740	543	Crushing	B 12y	324
B 12b	5 910	7 750	483	Tension	B 12z	454
B 12c	4 325	5 500	345	Tension		
B 12d	5 550	5 550	350	Tension		
B 13a	5 580	7 050	438	Crushing	B 13y	177
B 13b	6 125	7 650	478	Crushing	B 13z	519
B 13c	4 940	8 000	497	Tension		
B 13d	5 650	9 200	578	Tension		
B 14a	5 220	6 250	397	Tension	B 14y	393
B 14b	5 250	6 550	413	Tension	B 14z	362
Av.	6 110	8 280	513			393
D 1a	6 310	7 900	474	Crushing	D 1y	161
D 1b	5 920	8 000	491	Tension	D 1z	294
D 1c	5 180	6 450	389	Crushing		
D 1d	4 540	6 450	381	Tension		
D 2a	3 690	5 000	313	Crushing	D 2y	563
D 2b	5 740	7 000	424	Tension	D 2z	523
D 2c	2 990	3 800	234	Hor. Shear		
D 2d	4 410	5 600	347	Crushing		
D 3b	4 790	5 700	358	Tension	D 3y	451
D 3c	3 400	3 400	214	Tension	D 3z	400
D 3d	3 610	4 000	252	Tension		

TABLE 13. (Continued)
 TESTS OF MINOR TEST PIECES.
 Stresses are given in lb. per sq. in.

Small Beams, 3 x 3 x 40 inches					Shear Blocks Approximately 7 x 12 in.	
Des.	Elastic Limit	Fiber Stress	Hor. Shear'g Stress	Manner of Failure	Design- ation	Shearing Stress
D 4a	6 340	8 450	528	Crushing	D 4y	493
D 4b	5 500	8 300	520	Crushing	D 4z	600
D 4c	5 420	7 400	460	Crushing		
D 4d	4 910	6 100	382	Crushing		
D 6a	3 490	4 500	279	Tension	D 6y	327
D 6b	3 710	4 800	276	Tension	D 6z	359
D 6c	3 050	4 450	278	Tension		
D 6d	3 090	4 700	292	Crushing		
D 7b	5 900	8 300	512	Tension	D 7y	407
D 7c	5 620	7 400	468	Tension	D 7z	115
D 7d	5 370	7 200	451	Crushing		
D 8a	4 425	5 500	342	Tension	D 8y	286
D 8b	3 700	5 300	332	Tension	D 8z	390
D 8c	2 890	4 200	264	Crushing		
D 8d	3 010	4 700	297	Tension		
D 9a	4 330	6 500	406	Tension	D 9y	320
D 9b	5 180	6 000	369	Tension	D 9z	445
D 9c	4 510	6 100	383	Crushing		
D 9d	4 110	6 100	378	Tension		
D 10a	6 030	7 500	466	Crushing	D10y	481
D 10b	4 570	6 800	435	Crushing	D10z	348
D 10c	4 270	6 000	374	Crushing		
D 10d	4 200	5 900	367	Crushing		
D 11a	4 280	7 000	438	Tension	D11y	742
D 11b	4 580	6 100	387	Tension	D11z	557
D 11c	3 490	4 900	308	Crushing		
D 11d	3 540	5 100	318	Crushing		
D 12a	4 610	5 650	355	Crushing	D12y	430
D 12b	4 210	6 300	402	Crushing	D12z	513
D 12c	3 550	5 400	338	Tension		
D 12d	3 560	5 200	333	Tension		
D 13a	4 020	6 700	417	Tension	D13y	549
D 13b	5 310	6 700	407	Tension	D13z	415
D 13c	4 780	6 200	378	Crushing		
D 13d	4 500	6 600	397	Crushing		
D 14a	5 000	6 050	377	Hor. shear	D14y	143
D 14b	3 400	3 400	212	Hor. shear	D14z	176
D 14c	5 610	7 400	468	Tension		
D 14d	5 600	7 600	484	Crushing		
Av.	4 485	6 035	375			403
D 16a	1 470	1 880	114	Tension	D16y	406
D 16d	816	816	51	Tension	D16z	551
D 17a	4 000	4 670	292	Tension	D17y	412
					D17z	440
D 18a	4 850	4 850	304	Tension	D18y	227
D 18c	4 750	6 000	375	Tension	D18z	141

TABLE 13. (Continued)

TESTS OF MINOR TEST PIECES.

Stresses are given in lb. per sq. in.

Small Beams, 3 x 3 x 40 inches.					Shear Blocks Approximately 7 x 12 in.	
Des.	Elastic Limit	Fiber Stress	Hor. Shear's Stress	Manner of Failure	Design- nation	Shearing Stress
D 19a	7 060	9 000	552	Hor. shear	D19y	502
D 19b	6 010	6 060	380	Tension	D19z	254
D 19c	3 760	4 920	302	Hor. shear		
D 19d	3 600	4 340	271	Hor. shear		
D 20a	4 050	5 360	336	Tension	D20y	590
D 20b	4 310	6 400	402	Tension	D20z	556
D 20c	4 240	6 550	410	Tension		
D 20d	4 450	6 850	418	Crushing		
D 21a	5 730	7 540	472	Tension	D21y	647
D 21b	6 380	8 510	522	Tension	D21z	542
D 21c	4 180	4 570	298	Hor. Shear		
D 21d	5 020	5 060	309	Hor. Shear		
D 22a	7 450	8 400	526	Tension	D22y	450
D 22b	6 400	8 000	500	Hor. shear	D22z	479
D 22c	5 340	6 670	417	Tension		
D 22d	6 250	7 600	465	Tension		
D 23a	7 770	9 010	553	Crushing	D23y	163
D 23b	6 790	8 490	520	Tension	D23z	401
D 23c	5 675	7 750	474	Tension		
D 23d	5 090	7 230	443	Crushing		
D 24a	5 680	5 890	362	Tension	D24y	572
D 24b	5 090	7 120	438	Tension	D24z	483
D 24c	4 120	5 780	355	Tension		
D 24d	4 720	6 140	376	Tension		
D 25a	5 310	6 550	395	Tension	D25y	418
D 25b	4 150	5 190	319	Tension	D25z	448
D 25c	2 780	4 170	256	Tension		
D 25d	4 000	4 600	282	Tension		
D 26a	4 730	6 770	378	Tension	D26y	515
D 26b	6 100	7 270	445	Tension	D26z	498
D 26c	3 730	5 120	320	Tension		
D 26d	7 050	8 490	530	Tension		
Av.	4 945	6 210	383			441
E 1a	8 200	10 300	647	Hor. shear	E 1y	98
E 1b	4 560	8 950	565	Tension	E 1z	250
E 1c	8 270	10 300	647	Tension		
E 1d	8 700	11 200	704	Tension		
E 2a	7 290	9 800	613	Tension		
E 2b	9 150	12 100	758	Tension		
E 2c	6 975	7 900	495	Tension		
E 2d	9 300	9 300	582	Tension		
E 3a	8 950	9 350	583	Tension	E 3y	664
E 3b	9 300	10 250	641	Tension	E 3z	514
E 3c	5 330	7 200	348	Tension		
E 3d	4 080	7 650	478	Hor. shear		
E 4a	6 800	8 840	541	Tension	E 4y	535
E 4b	8 000	10 000	625	Hor. shear	E 4z	492
E 4c	7 270	10 170	683	Tension		
E 4d	7 680	10 170	650	Tension		

TABLE 13. (Continued)
 TESTS OF MINOR TEST PIECES.
 Stresses are given in lb. per sq. in.

Small Beams, 3 x 3 x 40 inches.					Shear Blocks Approximately 7 x 12 in.	
Des.	Elastic Limit	Fiber Stress	Hor. Shear'g Stress	Manner of Failure	Design- ation	Shearing Stress
E 5a	8 610	8 640	530	Tension	E 5y	792
E 5b	4 870	6 480	533	Tension	E 5z	529
E 5c	10 770	10 770	670	Crushing		
E 5d	8 160	11 480	718	Crushing		
E 6a	7 330	11 010	574	Tension	E 6y	354
E 6c	7 230	9 860	535	Tension	E 6z	318
E 6d	6 800	8 120	508	Tension		
E 7a	10 550	14 410	812	Crushing	E 7y	336
E 7b	6 950	8 820	539	Tension	E 7z	450
E 7c	7 220	10 200	625	Tension		
E 7d	6 860	9 380	583	Tension		
E 8a	8 780	12 820	802	Crushing	E 8y	293
E 8b	3 010	4 740	296	Tension	E 8z	375
E 8c	6 250	9 440	590	Hor. shear		
E 8d	7 450	9 450	592	Tension		
E 9a	5 470	7 270	454	Tension	E 9y	659
E 9b	6 790	9 460	592	Hor. shear	E 9z	511
E 9c	7 180	9 180	572	Tension		
E 9d	9 460	10 950	685	Tension		
E10a	8 240	10 020	626	Tension	E10y	635
E10b	4 960	5 300	331	Hor. shear	E10z	544
E10c	7 710	8 340	531	Tension		
E10d	8 430	11 780	743	Tension		
E11a	6 570	7 660	451	Hor. shear	E11y	611
E11b	7 970	9 680	607	Tension	E11z	695
E11c	2 230	3 130	189	Hor. shear		
E11d	6 670	8 860	541	Tension		
E12a	5 420	6 970	438	Tension	E12y	597
E12b	7 650	10 030	642	Tension	E12z	437
E12c	3 640	5 630	354	Tension		
E12d	6 650	8 920	558	Tension		
Av.	7 145	9 200	570			486
F 1a	4 489	4 600	294	Tension	F 1y	186
F 1b	6 780	7 200	448	Tension	F 1z	394
F 1c	3 740	5 150	323	Tension		
F 2a	6 375	7 650	486	Tension	F 2y	393
F 2b	3 020	3 280	206	Tension	F 2z	425
F 2c	4 850	5 650	352	Tension		
F 2d	4 430	4 700	287	Tension		
F 3a	7 950	9 400	588	Hor. shear	F 3y	229
F 3b	5 500	5 900	373	Tension	F 3z	171
F 3c	5 780	7 000	448	Crushing		
F 3d	5 100	6 350	403	Hor. shear		
F 4a	6 880	8 600	538	Crushing	F 4y	297
F 4b	6 300	7 600	478	Tension	F 4z	191
F 4c	6 070	7 900	501	Crushing		
F 4d	6 100	7 550	473	Crushing		

TABLE 13. (*Concluded*)

TESTS OF MINOR TEST PIECES.

Stresses are given in lb. per sq. in.

Small Beams, 3 x 3 x 40 inches.					Shear Blocks Approximately 7 x 12 in	
Des.	Elastic Limit	Fiber Stress	Hor. Shear'g Stress	Manner of Failure	Designa- tion	Shearing Stress
F 9a	8 950	10 510	660	Crushing	F 9y	447
F 9b	6 510	7 840	472	Hor. shear	F 9z	499
F 9c	8 510	9 550	586	Tension		
F 10a	6 670	8 930	558	Hor. shear	F10y	362
F 10b	7 340	7 650	478	Hor. shear	F10z	340
F 10c	5 880	8 540	535	Tension		
F 10d	3 320	5 370	336	Tension		
F 11a	5 930	7 330	443	Tension	F11y	303
F 11b	7 390	8 660	519	Tension	F11z	891
F 11c	6 650	9 470	578	Tension		
F 11d	5 890	6 530	393	Tension		
F 12a	5 940	8 970	549	Tension	F12y	500
F 12b	5 270	6 940	426	Tension	F12z	262
F 12c	5 940	8 420	515	Crushing		
F 12d	5 080	7 600	465	Tension		
F 13a	6 780	9 200	552	Tension	F13y	236
F 13b	5 380	6 930	469	Tension	F13z	342
F 13c	5 690	7 650	470	Tension		
F 13d	6 380	6 620	406	Tension		
F 14a	5 275	6 200	381	Tension	F14y	179
F 14b	5 800	8 850	541	Tension	F14z	222
F 14c	5 640	7 550	463	Tension		
F 14d	5 470	6 670	416	Tension		
F 15a	6 660	6 940	426	Tension	F15y	234
F 15b	6 250	7 520	462	Tension	F15z	273
F 15c	5 830	8 480	521	Crushing		
F 15d	5 460	7 520	472	Tension		
F 16a	5 825	8 270	507	Tension	F16y	320
F 16b	6 270	8 660	513	Crushing	F16z	364
F 16c	6 520	7 570	454	Tension		
F 16d	6 650	6 860	402	Tension		
Av.	5 970	7 445	460			315

difference in depth in Series A and B, and the small number of pieces in some of the series. Reference to this table will be made in the discussion which follows.

18. *Test Data of Miscellaneous Test Pieces. Series M and N.*—In Table 15 are given the data of the tests of series M. The test pieces were taken from four stringers, and by an oversight all pieces were creosoted. However, the results are of some interest in showing the variations in test pieces cut from the same stringer and in the averages for the several stringers. The individual variations in the small beams, both in elastic limit and in

TABLE 14.

SUMMARY OF RESULTS OF TESTS.

All stresses are given in lb. per sq. in.

	Series A Longleaf Pine	Series B Longleaf Pine	Series C						Series D Loblolly Pine		Series E Old Douglas Fir	Series F New Douglas Fir
			Shortleaf Pine		Loblolly Pine		Un- treated	Creo- soted	Un- treated	Creo- soted		
			Un- treated	Creo- soted	Un- treated	Creo- soted						
Number of stringers tested.....	20	14	4	8	4	8	14	12	12	16		
Percentage of horizontal shear failures.....	60	93	100	75	75	62	50	25	83	69		
Percentage of tension and compression failures.....	40	7	0	25	25	38	50	75	17	31		
Average horizontal shearing stress at failure.....	344	386	364	302	368	257	289	330	291	315		
Average fiber stress at elastic limit.....	4336	4392	4343	3386	4164	2330	2960	3587	3823	3955		
Average fiber stress at failure.....	5308	5470	4886	4078	4936	3446	4090	4748	4284	4544		
Falling by horizontal shear:												
Average horizontal shearing stress at failure...	370	390	364	302	379	273	314	363	298	323		
Lowest horizontal shearing stress at failure....	188	237	293	224	368	224	253	320	221	275		
Highest horizontal shearing stress at failure....	497	474	505	410	388	368	381	391	383	401		
Average fiber stress at failure.....	5527	5483	4886	4082	5082	3687	4387	5193	4403	4751		
Lowest fiber stress at failure.....	2640	3620	4005	3025	4890	3020	3760	4460	3320	3990		
Highest fiber stress at failure.....	7260	6540	6810	5550	5195	4915	5740	6020	5730	6040		
Falling by tension or compression:												
Average horizontal shearing stress at failure..	306	344		302	334	229	263	319	252	293		
Highest horizontal shearing stress at failure...	471	344		357	334	243	326	420	282	355		
Average fiber stress at failure.....	4978	5300		4067	4500	3043	3794	4600	3690	4088		
Lowest fiber stress at failure.....	960	5300		3405	4500	2870	2530	2660	3260	3250		
Highest fiber stress at failure.....	8410	5300		4730	4500	3175	5130	6080	4120	5180		
Small beams. Average horizontal shearing stress	550	513					375	383	570	460		
Small beams. Average fiber stress at elastic limit	6835	6110					4485	4945	7145	5970		
Small beams. Average fiber stress at failure.....	8810	8280					6035	6210	9200	7445		
Shear blocks. Average shearing stress.....	466	393					403	441	486	315		

ultimate strength, are not large. The variations in strength of shear blocks are more noticeable, ranging from 45% below the average for the stringer to 60% above that average. The values, 1130, 1035, and 1011 lb. per sq. in., are especially high for loblolly pine, and 241 and 244 lb. per sq. in. are low strengths for shear blocks. Of the averages for test pieces from one stringer, the high value for elastic limit and maximum fiber stress in the small beams in M 4, 6215 and 8735 lb., respectively, may be noted, and also the low value for its shear blocks, 442 lb. per sq. in.

In Table 16 are given the data for the tests of Series N. A comparison of the results for the untreated and treated pieces is made under "26. Effect of Creosoting". The general uniformity of the results in the small test beams cut from the same stringer is noticeable. Two low values, N1a4 and N4c4, are shown by the notes to be due to knots and cross grain. The strength of the shear blocks covers a greater range. The high values are 1106, 1004, and 1014 lb. per sq. in. The low values are 217 and 277 lb. per sq. in. The average maximum fiber stress for the small beams in N2 and N3 is high.

19. *Horizontal Shearing Strength.*—Table 17 gives a summary of the results of the failures in horizontal shear. Fig. 8 is given to show the range and the distribution of the results over the field. The large number of failures by horizontal shear and the seemingly low values found for the shearing resistance, as compared with those quoted in books and with the results obtained from small test specimens, are worthy of note. The method of selection of stringers and the variety of conditions represented indicate that the stringers are not unusual lots and that so far as resistance to shear is concerned their general condition may be considered to be similar to that of timber in use. The range of results is from 188 to 497 lb. per sq. in., and the average for the several series runs from 273 to 390 lb. per sq. in. It is worthy of note in this connection that, as a general rule, for the stringers which did not fail in horizontal shear those developing a shearing stress less than the average for the series had defects like knots which obviously were the occasion of the low cross-breaking strength and that those not showing such defects gave shearing stresses not as high as the highest developed in shear failures. It is also interesting to note that in the stringer which developed the highest fiber stress, A17, the break in tension was

TABLE 15.
TESTS OF SERIES M.

All creosoted loblolly pine. All failed in tension. Stresses are given in lb. per sq. in.

Small Beams, 3 x 3 x 40 in.				Shear Blocks Approximately 7 x 12 in.	
Des.	Elastic Limit	Fiber Stress	Hor. Shearing Stress	Des.	Shearing Stress
M 1a1	5 760	8 150	510	M 1b1	1130
M 1a1	3 760	6 850	436	M 1b2	884
M 1a2	6 000	8 850	542	M 1b3	718
M 1a2	5 870	7 700	481	M 1b4	464
M 1a3	5 020	7 000	445	M 1b5	523
M 1a3	5 130	7 060	449	M 1b6	780
M 1a4	4 650	6 480	405	M 1b7	
M 1a4	5 110	7 200	450	M 1b8	464
M 1c1	5 240	7 040	438	M 1b9	746
M 1c1	5 660	7 690	480	M 1b10	582
M 1c2	4 140	6 460	404	M 1b11	
M 1c2	4 270	6 800	424	M 1b12	954
M 1c3	4 750	7 300	446	M 1b13	
M 1c3	4 730	7 750	484	M 1b14	561
M 1c4	5 450	7 400	471		
M 1c4	4 000	6 660	409		
Av.	4 975	7 275	454		710
M 2a1	5 440	7 800	489	M 2b1	863
M 2a1	5 230	8 500	531	M 2b2	955
M 2a2	4 610	6 710	428	M 2b3	664
M 2a2	5 160	6 920	440	M 2b4	682
M 2a3	4 260	5 350	334	M 2b5	766
M 2a3	4 260	5 730	358	M 2b6	
M 2a4	5 040	6 200	394	M 2b7	
M 2a4	4 480	6 380	406	M 2b8	436
M 2c1	5 520	9 280	590	M 2b9	650
M 2c1	6 800	8 550	544	M 2b10	965
M 2c2	5 900	8 270	526	M 2b11	678
M 2c2	5 020	6 280	400	M 2b12	864
M 2c3	5 360	7 100	444	M 2b13	908
M 2c3	4 150	6 530	414	M 2b14	875
M 2c4	5 930	8 310	528		
M 2c4	5 070	6 490	405		
Av.	5 135	7 160	452		775
M 3a1	3 590	4 740	296	M 3b1	646
M 3a1	4 170	5 450	345	M 3b2	766
M 3a2	3 720	5 650	360	M 3b3	478
M 3a2	4 700	5 830	364	M 3b4	465
M 3a3	4 900	4 900	306	M 3b5	297
M 3a3	4 180	4 760	304	M 3b6	343
M 3a4	4 400	6 350	397	M 3b7	761
M 3a4	5 350	7 100	443	M 3b8	562
M 3c1	5 550	7 360	479	M 3b9	467
M 3c1	5 020	5 400	344	M 3b10	
M 3c2	6 890	7 650	478	M 3b11	
M 3c2	4 100	6 770	424	M 3b12	892
M 3c3	5 150	7 280	463	M 3b13	1035
M 3c3	5 540	7 550	490	M 3b14	1011
M 3c4	6 280	7 850	499		
M 3c4	5 130	7 550	481		
Av.	4 915	6 390	405		643

TABLE 15—(Concluded)

TESTS OF SERIES M.

All creosoted loblolly pine. All failed in tension. Stresses are given in lb. per sq. in.

Small Beams, 3 x 3 x 40 in.				Shear Blocks Approximately 7 x 12 in.	
Des.	Elastic Limit	Fiber Stress	Hor. Shearing Stress	Des.	Shearing Stress
M 4a1	7 450	7 840	490	M 4b1	358
M 4a1	6 150	7 060	450	M 4b2	241
M 4a2	6 800	7 960	498	M 4b3	496
M 4a2	6 150	7 600	474	M 4b4	276
M 4a3	5 670	7 850	498	M 4b5	244
M 4a3	5 550	9 790	612	M 4b6	281
M 4a4	7 850	10 140	645	M 4b7	460
M 4a4	5 960	8 120	516	M 4b8	480
M 4c1	5 760	8 840	564	M 4b9	740
M 4c1	6 530	9 860	616	M 4b10	563
M 4c2	5 080	7 800	486	M 4b11	
M 4c2	6 410	8 810	563	M 4b12	
M 4c3	6 790	10 400	650	M 4b13	626
M 4c3	4 800	8 800	550	M 4b14	541
M 4c4	6 800	9 460	591		
M 4c4	5 690	9 390	586		
Av.	6 215	8 735	549		442

followed so quickly by horizontal shear failure that only direct observation at the instant of failure enabled the initial cause of failure to be known. Only three beams developed a higher shearing resistance than this, and their failures were by horizontal shear.

It is of interest to compare the shearing resistance developed in the stringers with the results of the shear tests of blocks cut from the stringers. These shear blocks were the full thickness of the stringer and were taken from the mid-depth at an uninjured end. Thus, although they represented the portion of the depth which received the greatest shearing stress, in the case of stringers which had failed by shear, the blocks presumably had greater shearing strength than had the timber at the end which failed. As the shear blocks contained seasoning checks and other defects, the results may be expected to be less than those which would be obtained from small pieces of selected wood or from pieces taken away from the heart wood. Table 18 gives the ratio of the horizontal shearing stress developed in the stringers to the shearing stress developed in the shear blocks. It will be seen that this ratio, in the case of stringers failing in horizontal

TABLE 16.

TESTS OF SERIES N.

Loblolly pine. Even numbers are creosoted. Odd numbers are untreated.
Stresses are given in lb. per sq. in.

Small Beams, 3 x 3 x 40 inches.					Shear Blocks Approximately 7 x 12 in.	
Des.	Elastic Limit	Fiber Stress	Hor. Shear'g Stress	Manner of Failure	Des.	Shearing Stress
N1a1	5 060	7 960	498	Tension	N1b1	956
N1a1	4 780	7 950	477	No break	N1b2	841
N1a2	3 600	6 020	376	Tension	N1b3	
N1a2	4 000	5 020	314	Tension	N1b4	757
N1a3	5 490	7 350	459	Tension	N1b5	803
N1a3	4 540	7 760	485	Tension	N1b6	920
N1a4	4 400	5 750	367	Tension	N1b7	878
N1a4	2 350	2 350*	156	Tension	N1b8	696
N1c1	3 840	8 550	545	Tension	N1b9	1106
N1c1	4 480	6 280	400	Tension	N1b10	709
N1c2	4 130	6 040	385	Tension	N1b11	
N1c2	4 260	6 400	400	Tension	N1b12	889
N1c3	4 575	7 550	482	Tension	N1b13	
N1c3	6 660	9 600	600	Tension	N1b14	1004
N1c4	3 780	5 550	353	Tension	N1b15	968
N1c4	3 770	6 720	429	Tension	N1b16	935
Average Untreated	4 930	7 875	493			942
Average Creosoted	3 785	5 480	348			844
N2a1	7 900	11 400	714	Tension	N2b1	671
N2a1	7 460	11 300	706	Tension	N2b2	715
N2a2	5 750	8 310	530	Crushing	N2b3	
N2a2	6 790	8 820	552	Tension	N2b4	611
N2a3	6 150	9 520	607	Tension	N2b5	904
N2a3	6 550	9 800	612	Tension	N2b6	692
N2a4	5 960	7 850	500	Tension	N2b7	865
N2a4	4 790	6 670	425	Tension	N2b8	672
					N2b9	827
					N2b10	552
N2c2	5 520	8 580	546	Tension	N2b11	
N2c2	8 540	10 900	655	Tension	N2b12	632
N2c3	5 790	8 630	550	Tension	N2b13	745
N2c3	6 550	9 080	578	Tension	N2b14	594
N2c4	5 300	8 200	524	Tension	N2b15	737
N2c4	4 230	5 950	379	Tension	N2b16	755
Average Untreated	6 730	9 955	628			791
Average Creosoted	5 860	8 160	514			653
N3a1	6 650	10 040	640	Tension	N3b1	612
N3a1	6 420	8 550	545	Tension	N3b2	739
N3a2	5 220	7 600	475	Tension	N3b3	794
N3a2	5 340	9 420	600	Tension	N3b4	791
N3a3	6 380	10 200	639	Tension	N3b5	877
N3a3	6 000	9 750	609	Tension	N3b6	775
N3a4	4 710	7 100	452	Tension	N3b7	451
N3a4	5 650	8 090	515	Tension	N3b8	517

* Low value is due to knots and cross grain.

TABLE 16. (*Concluded*)

TESTS OF SERIES N.

Loblolly pine. Even numbers are creosoted. Odd numbers are untreated.
Stresses are given in lb. per sq. in.

Small Beams, 3 x 3 x 40 inches.					Shear Blocks Approximately 7 x 12 in.	
Des.	Elastic Limit	Fiber Stress	Hor. Shear's Stress	Manner of Failure	Des.	Shearing Stress
N3c1	6 925	10 800	688	Tension	N3b9	718
N3c1	5 650	9 760	622	Tension	N3b10	277
N3c2	4 810	7 270	464	Crushing	N3b11	423
N3c2	6 400	8 810	562	Tension	N3b12	634
N3c3	5 930	9 450	615	Tension	N3b13	....
N3c3	6 040	8 580	546	Tension	N3b14	617
N3c4	5 250	7 400	462	Tension	N3b15	714
N3c4	5 560	8 190	521	Crushing	N3b16	831
Average Untreated	6 250	8 640	613			656
Average Creosoted	5 370	7 985	506			648
					N4b1	626
N4a2	5 780	8 150	520	Tension	N4b2	717
N4a2	6 170	8 760	558	Tension	N4b3	644
N4a3	6 150	9 100	580	Tension	N4b4	633
N4a3	6 460	9 600	625	Crushing	N4b5	528
N4a4	5 180	7 000	446	Tension	N4b6	524
N4a4	5 150	7 210	460	Tension	N4b7	792
					N4b8	425
N4c1	4 660	8 000	500	Tension	N4b9	858
N4c1	4 860	8 040	512	Tension	N4b10	1014
N4c2	3 840	5 570	355	Tension	N4b11	922
N4c2	3 540	6 280	385	Tension	N4b12	922
					N4b13	....
N4c4	3 520	5 910	377	Tension	N4b14	807
N4c4	2 860	3 240*	198	Tension	N4b15	678
					N4b16	217
Average Untreated	5 530	8 685	554			721
Average Creosoted	4 505	6 515	412			656

* Low value is due to knots and cross grain.

shear, ranged from 0.61 for Series E to 1.00 for Series F. It seems evident that a lower shearing resistance may be expected in beams than will be developed in shear tests on blocks taken as these were.

Attention is called to the higher shearing stresses developed in the small beams taken from the top and bottom of the tested stringers, as shown in Table 13, even when the failure was by tension or compression, and to the fact that the shearing stress developed in the small beams averaged higher than the shearing strength

TABLE 17.

SUMMARY OF FAILURES IN HORIZONTAL SHEAR.

Stresses are given in lb. per sq. in. In the last column is given the highest value for stringers which did not fail by horizontal shear.

Series and Kind	No. of Pieces	Horizontal Shearing Stress			Highest Stress in other Stringers
		Average	Highest	Lowest	
A Untreated longleaf pine.....	12	370	497	188	471
B Untreated longleaf pine.....	13	390	474	237	344
C Untreated shortleaf pine.....	4	364	505	293	...
C Creosoted shortleaf pine.....	6	302	410	224	357
C Untreated loblolly pine.....	3	379	388	368	334
C Creosoted loblolly pine.....	5	273	368	224	243
D Untreated loblolly pine.....	7	314	381	253	326
D Creosoted loblolly pine.....	3	363	391	320	420
E Old Douglas fir.....	10	298	383	221	282
F New Douglas fir.....	11	323	401	275	355

TABLE 18.

RELATION OF HORIZONTAL SHEARING STRESS DEVELOPED IN STRINGERS
TO STRESS DEVELOPED IN SHEAR BLOCKS CUT FROM
UNINJURED PORTION OF STRINGERS.

Stresses are given in lb. per sq. in.

Series and Kind	Stringers Failing in Shear				All Stringers			
	No. of Pieces	Hor. Shearing Stress			No of Pieces	Hor. Shearing Stress		
		String-ers	Blocks	Ratio		String-ers	Blocks	Ratio
A Untreated longleaf pine.....	12	370	491	.75	20	344	466	.74
B Untreated longleaf pine.....	13	390	394	.99	14	386	393	.98
D Untreated loblolly pine.....	7	314	384	.82	14	289	403	.72
D Creosoted loblolly pine.....	3	363	483	.75	12	330	441	.75
E Old Douglas fir.....	10	298	491	.61	12	291	486	.60
F New Douglas fir.....	11	323	321	1.01	16	315	315	1.00

of the shear block taken from the same stringer except for Series D which was loblolly pine having a low fiber strength and hence developing a correspondingly low shearing stress in the beams tested. This comparison brings out the greater shearing resistance of the wood at the top and bottom of the stringer in timber subject to seasoning checks of magnitude.

In examining the results of these tests it is apparent that seasoning checks are a source of weakness in horizontal shearing

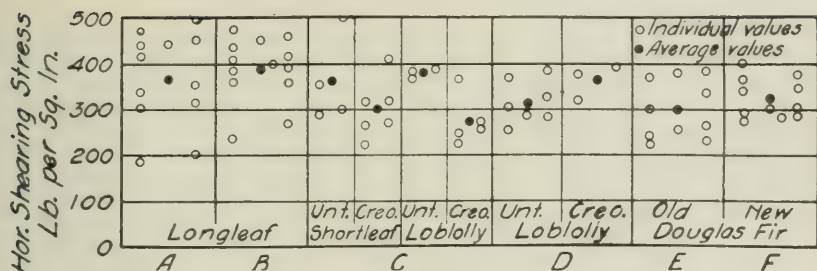


FIG. 8. VALUES OF HORIZONTAL SHEARING STRESS IN BEAMS FAILING IN HORIZONTAL SHEAR.

resistance and that a wood which develops marked seasoning checks, as longleaf pine, may have its higher tensile and compressive strength discounted by shearing weaknesses, while a softer wood like loblolly pine in beams of the dimensions used in stringers may more advantageously utilize the fiber strength it possesses. It is well to emphasize the importance of using methods of seasoning which will minimize the evil of the checks and cracks produced in seasoning.

As having a possible bearing on whether the greater exposure at the end of the stick may develop more troublesome seasoning checks than are developed in the remainder of the stick, the tests of the Douglas fir stringers may be examined. These stringers came in lengths of 32 ft. and were cut at the middle to make two test beams, thus giving one old end and one new end. Of the old Douglas fir which failed in horizontal shear, six failed at the new end and two at the old end, and for the other two there is no record. Of the new Douglas fir which failed in horizontal shear, two failed at the new end and seven at the old end, and for two there is no record.

20. *Maximum Fiber Stress.*—The maximum fiber stress developed in the full-size beams was generally low, lower than the values generally quoted for the strength of such timber. The shear failures, of course, operated to prevent the development of the full fiber strength of the wood, but it is worthy of note (see Table 14) that in every series the average value of the fiber stress developed in beams failing in tension was less than the average in beams failing in horizontal shear, and that with the exception of Series A the highest fiber stress developed was less in the tension failures than in the shear failures. That the reason for

low fiber strength may lie principally in the presence of knots and cross-grain emphasizes rather than detracts from the importance of these deductions.

The average value of the maximum fiber stress is, in the several series, from 3445 lb. per sq. in. in the creosoted loblolly pine of Series D to 5470 lb. per sq. in. in the longleaf pine of Series A. The high values, as may be expected, are generally in clear, straight-grained heavy sticks, though A17 which developed a maximum fiber stress of 8410 lb. per sq. in., the highest strength of any beam tested, contained a number of solid knots, $\frac{3}{4}$ in. to $1\frac{3}{4}$ in. across, all at or near the upper surface of the beam. The low values in cross-breaking failures were found in sticks having defects like large knots, cross grain, or in the case of the loblolly pine a large amount of sap wood. In most of the very low values in cross breaking the defects in the sticks were quite apparent, as in the two sticks in Series C which were selected to show the effect of large knots and as in D5 and D16 which would hardly be called merchantable sticks, but in A4 (see Plate 1) the bad shake through the middle of the length of the beam could not have been known in advance of the test.

Tests show that selected wood is stronger and stiffer in tension than in compression, but it is seen that the failures in cross bending were generally on the tension side. The exceptions are in the creosoted loblolly in Series D. It will be shown that in Series C the deformation on the tension face of the beams was greater than on the compression face. These facts seem to indicate that the defects of knots and cross grain have a greater effect on the properties of tension than on those of compression. Possibly another explanation may be found for the conditions in loblolly pine.

Fig. 9 shows for the several series the distribution of the maximum fiber stress developed, a distinction being made between cross-breaking and shear failures.

21. *Relation of Fiber Stress of Small and Full-size Pieces.*—It is evident from Table 19 that the small test beams taken from the top and bottom of the full-size stringers developed much higher stresses than were developed in the tests of the stringers. This was true in the fiber strength of the small test beams which failed in tension or compression and also in the shearing strength developed in the beams failing in horizontal shear. The higher fiber

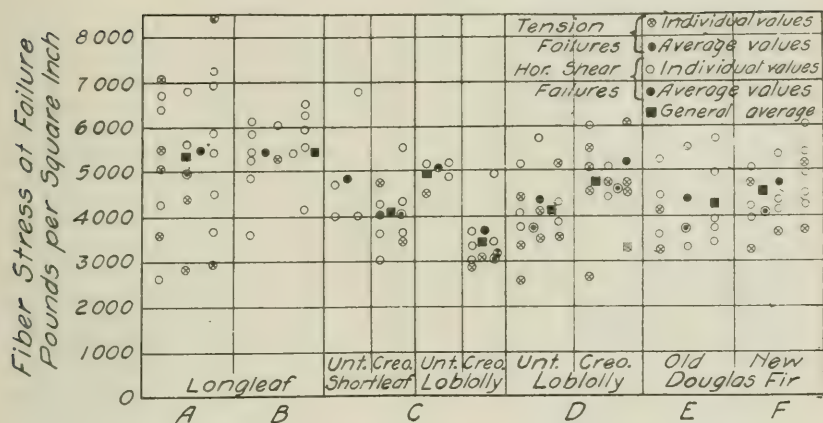


FIG. 9. VALUES OF FIBER STRESS AT FAILURE.

stress developed in the small beams may be due in part to the greater freedom from knots in the small test beams selected than in the large stringers, but a large part may be attributed to greater homogeneity of structure in the small beams and to the absence of seasoning checks. The higher horizontal shearing stress developed in the small beams may be due principally to the greater freedom from seasoning checks and the consequent greater resistance of the fibers to longitudinal shear.

The comparison of the fiber stresses developed in cross bending at failure given in Table 19 shows that the fiber stress of the full-size stringers averaged in the several series from 48% to 76% of the fiber stress in the corresponding small test beams. Even with the failures by horizontal shear excluded from consideration, the relation would be but little better. In Series C a systematic test of small beams was not made, but the small beams taken from four of the full-size beams showed the latter to have 47% to 55% of the strength of the former in the case of the shortleaf pine and 76% to 83% in the case of the loblolly pine. Few of the small test beams failed by horizontal shear, but the shearing strength developed in the small beams was much higher than in the large ones.

The results of the tests as a whole go to show, if it were necessary to have a new confirmation of this, that the strength of small pieces may not be taken as representative of the strength of full-size sticks. Tests of small pieces may be of service in comparing woods of different kinds, though even here one species or

TABLE 19.

RELATION OF MAXIMUM FIBER STRESS DEVELOPED IN STRINGERS TO
STRESS DEVELOPED IN SMALL TEST BEAMS.

Stresses are given in lb. per sq. in.

Series and Kind	Average			Highest			Lowest		
	Large	Small	Ratio	Large	Small	Ratio	Large	Small	Ratio
A Unt. longleaf pine....	5308	8810	.60	8410	11500	.73	2640	10000	.26
B Unt. longleaf pine....	5170	8280	.66	6470	9850	.66	3620	7410	.49
D Unt. loblolly pine....	4090	6035	.68	5740	8450	.68	2530		
D Creo. loblolly pine....	4748	6210	.76	6080	9000	.68	2660	1880	1.42
E Old Douglas fir.....	4284	9200	.47	5730	10950	.52	3260	5300	.62
F New Douglas fir.....	4544	7445	.61	6040	10510	.57	3250		

one shipment may be more subject to the weakness of knots, shakes, or seasoning checks than another. The high values of fiber strength and of horizontal shearing strength sometimes given in tables in engineering books and literature seem to have crept in through assuming that the strength of small test-pieces represents the strength of the full-size stick which would be used.

22. *Elastic Limit.*—Table 20 gives the fiber stress at the elastic limit and the ratio of this stress to the stress at the ultimate. Failures by horizontal shear are grouped separately from cross-breaking failures, the former preceding the latter in the table. There is a considerable range in the value of the elastic limit. In Series C the range is from 1960 to 5830 lb. per sq. in.; in Series D from 1460 to 4330 lb. per sq. in. The elastic limit is evidently affected by defects like knots and cross grain. To what extent it is affected by conditions, like seasoning checks, which give low horizontal shearing strength or act to permit considerable longitudinal movement of fibers, is not known. The ratio of the elastic limit to the breaking strength is given in the column of ratios in Table 20. The average of the ratios is from 0.67 to 0.90.

Fig. 10 shows for the several series the elastic limits developed. It shows graphically the distribution of individual values over the field.

23. *Deflection of Beams and Modulus of Elasticity.*—The deflections at mid-span are shown in the diagrams in Fig. 11 to 19 at the end of the text. Since stringers are usually placed side by side, their relative stiffness fixes the proportion of the total load which the individual stringer takes; i. e., for a given deflection the stiffer stringer takes the larger share of the load and the less

TABLE 20.

RELATION OF FIBER STRESS AT ELASTIC LIMIT TO FIBER STRESS AT FAILURE.

Stresses are given in lb. per sq. in.

Des.	Elastic Limit	Ratio to Maximum	Des.	Elastic Limit	Ratio to Maximum	Des.	Elastic Limit	Ratio to Maximum
A 1	1960	.74	C 5	3165	.87	D 20	4330	.97
A 2	3060	.68	C 6	3620	.84	D 21	4280	.71
A 3	5480	.93	C 7	2360	.64	D 23	4510	.88
A 5	4820	.86	C 8	4065	.94			
A 7	3890	.90	C 9	2715	.90	Av.	4373	.85
A 8	5630	.84	C 12	4970	.90			
A 11	5720	.84				D 15	3680	.78
A 12	5700	.82	Av.	3482	.85	D 16	1460	.55
A 13	5440	.75				D 17	3530	.70
A 15	3610	.98	C 10	3660	.77	D 18	3600	.72
A 18	5200	.81	C 11	2530	.74	D 19	4020	.66
A 20	5310	.97				D 22	3570	.65
Av.	4652	.84	Av.	3095	.76	D 24	4180	.92
						D 25	2500	.76
A 4	3150	.88	C 13	3900	.76	D 26	3380	.74
A 6	2570	.90	C 15	3940	.80			
A 9	4060	.74	C 16	4900	.94	Av.	3324	.72
A 10	2940	1.00	Av.	4247	.83			
A 14	3010	.68				E 1	3050	.92
A 16	5830	.83	C 14	3915	.87	E 2	5360	.97
A 17	5800	.69				E 3	4970	.94
A 19	3540	.70	Av.	3915	.87	E 4	3260	.86
						E 5	3160	.92
Av.	3862	.80	C 17	2710	.79	E 6	3490	.97
			C 18	2155	.64	E 7	2960	.76
B 1	4180	.86	C 19	2670	.72	E 9	5090	.89
B 2	5020	.85	C 20	2180	.72	E 11	4660	.94
B 3	5080	.81	C 24	2795	.57	E 12	3500	.78
B 4	5160	.95				Av.	3950	.90
B 5	4560	.74	Av.	2502	.69			
B 6	5110	.84				E 8	4120	1.00
B 7	4150	.79	C 21	1930	.67	E 10	2260	.69
B 8	3720	.68	C 22	2180	.69			
B 9	3440	.95	C 23	2018	.66	Av.	3190	.84
B 10	4720	.72						
B 11	3960	.95	Av.	2043	.67	F 1	3730	.88
B 12	4860	.81				F 2	3420	.86
B 13	3970	.71	D 1	3820	.74	F 3	3940	.93
Av.	4456	.82	D 4	3730	.65	F 4	3410	.82
			D 9	3370	.87	F 5	4980	.98
B 14	3560	.67	D 10	2950	.78	F 6	4890	.98
Av.	3560	.67	D 12	2940	.72	F 9	4700	.78
			D 13	3100	.72	F 11	4080	.90
C 1	....	...	D 14	3320	.88	F 12	4250	.80
C 2	3780	.94	Av.	3320	.77	F 13	4020	.92
C 3	4310	.91				F 15	4370	.81
C 4	4940	.72	D 2	2790	.68	Av.	4163	.88
Av.	4343	.86	D 3	2180	.65			
			D 5	1950	.77	F 7	2920	.79
			D 6	2160	.61	F 8	2550	.78
			D 7	3660	.71	F 10	3180	.87
			D 8	2620	.75	F 14	4280	.91
			D 11	2830	.64	F 16	4560	.88
			Av.	2598	.69	Av.	3498	.85

stiff stringer receives a smaller share. In the several series the stiffness of the beams (a property which may be considered to vary as the reciprocal of the modulus of elasticity) ranged from, say, 0.75 of the average stiffness for the series to, say, 1.25 times

the average stiffness. A weak stringer, if placed beside an average stringer of its kind, would then take 75% of the load carried by the average stringer, or 86% of its half of the load. A stiff stringer, if placed beside an average stringer of its kind, would take 125% of the load carried by the average stringer, or 111% of its half of the load. As the tests show that the stringers with low carrying strength were generally less stiff than the strongest sticks, this variation may be considered to be helpful when sticks having defects are placed beside good timber. A 6, C 11, D 5, and D 16 may be cited as examples where large knots and poor grain acted to give low stiffness and low strength. The stiffness of A 6 was only 67% of the average of its series, and D 16 only 47%.

The modulus of elasticity of the full-size beams is given in Table 21. It was calculated from the deflection for the straight portion of the deflection curve, using the formula for center deflection, $\frac{23}{1296} \frac{Wl^3}{EI}$, given on page 7. The extremely low values are in sticks having large knots and cross grain. With the exception of a few values, the modulus of elasticity in each series is fairly uniform.

In the tests in Series C the deformation of the top and the bottom fiber along the middle of the beam was measured, as already described. The fiber stress was calculated by the usual beam formula, and from this calculated fiber stress and the measured deformations the modulus of elasticity for the top and bottom fiber was calculated. The results are given in Table 22, together with the modulus of elasticity determined from the deflections. In making comparisons it must be borne in mind that the formula for fiber stress and that for deflection are based upon the assumption of a uniform and homogeneous beam and also that the horizontal shearing deformations are neglected. The modulus of elasticity obtained from the deformation of the bottom fiber averages somewhat less than that obtained from the deformation of the top fiber, and the average modulus of elasticity obtained from the deflections is markedly less than either. It would be interesting to know what part of this difference is due to horizontal shearing action and what part to variability of the wood from heart to outer fiber.

Table 23 gives the modulus of elasticity of the small beams taken from the stringers of Series A, B, D, E, and F. The

TABLE 21.
MODULUS OF ELASTICITY OF TIMBER STRINGERS.
Values are given in lb. per sq. in.

Series A		Series B		Series C		Series C		Series D		Series D		Series E		Series F	
Des.	E	Des.	E	Des.	E	Des.	E	Des.	E	Des.	E	Des.	E	Des.	E
A 1	1 795 000	B 1	1 378 000	C 1	1 590 000	C 13	1 590 000	D 1	1 406 000	D 15	1 386 000	E 1	1 310 000	F 1	1 274 000
A 2	1 894 000	B 2	1 694 000	C 2	1 595 000	C 14	1 474 000	D 2	1 327 000	D 16	1 611 000	E 2	2 050 000	F 2	1 113 000
A 3	1 653 000	B 3	1 636 000	C 3	1 595 000	C 15	1 645 000	D 3	1 186 000	D 17	1 291 000	E 3	2 087 000	F 3	1 650 000
A 4	1 461 000	B 4	2 105 000	C 4	1 585 000	C 16	1 570 000	D 4	1 915 000	D 18	1 377 000	E 4	1 840 000	F 4	1 618 000
A 5	1 610 000	B 5	2 000 000					D 5	944 000	D 19	1 677 000	E 5	1 684 000	F 5	1 900 000
A 6	1 025 000	B 6	1 615 000	AV.	1 591 000	AV.	1 570 000	D 6	1 068 000	D 20	1 193 000	E 6	1 700 000	F 6	1 716 000
A 7	1 696 000	B 7	1 538 000					D 7	1 428 000	D 21	1 410 000	E 7	1 900 000	F 7	1 325 000
A 8	1 480 000	B 8	1 475 000	C 5	1 224 000	C 17	1 150 000	D 8	1 070 000	D 22	1 857 000	E 8	1 852 000	F 8	1 138 000
A 9	1 473 000	B 9	1 705 000	C 6	1 325 000	C 18	1 060 000	D 9	1 500 000	D 23	1 657 000	E 9	1 785 000	F 9	1 615 000
A 10	1 238 000	B 10	1 878 000	C 7	1 045 000	C 19	1 020 000	D 10	1 523 000	D 24	1 582 000	E 10	1 426 000	F 10	1 582 000
A 11	1 914 000	B 11	1 518 000	C 8	1 350 000	C 20	1 130 000	D 11	1 180 000	D 25	940 000	E 11	1 930 000	F 11	1 610 000
A 12	1 620 000	B 12	1 577 000	C 9	1 225 000	C 21	975 000	D 12	1 363 000	D 26	1 368 000	E 12	1 733 000	F 12	1 495 000
A 13	1 795 000	B 13	1 618 000	C 10	1 300 000	C 22	1 030 000	D 13	1 367 000					F 13	1 542 000
A 14	1 472 000	B 14	1 304 000	C 11	1 887 000	C 23	1 132 000	D 14	1 386 000					F 14	1 400 000
A 15	1 714 000			C 12	1 478 000	C 24	1 095 000							F 15	1 461 000
A 16	1 842 000			AV.	1 229 000	AV.	1 083 000							F 16	1 510 000
A 17	1 596 000														
A 18	1 704 000														
A 19	1 216 000														
A 20	1 810 000														
AV.	1 537 000	AV.	1 648 000	AV.	1 229 000	AV.	1 083 000	AV.	1 333 000	AV.	1 363 000	AV.	1 780 000	AV.	1 493 000

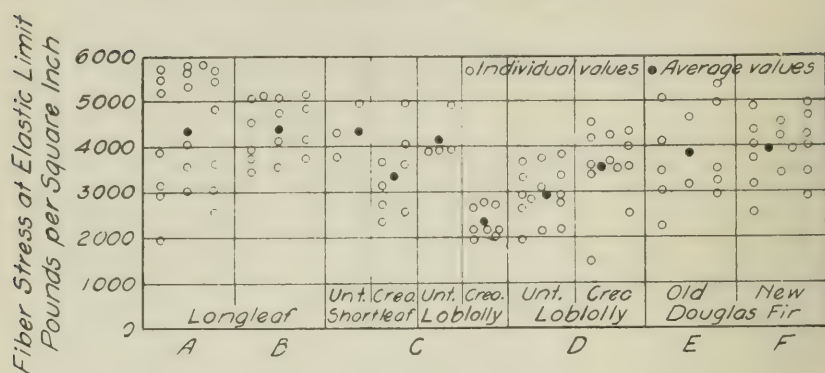


FIG. 10. VALUES OF FIBER STRESS AT ELASTIC LIMIT.

values are calculated from the center deflections, typical load-deflection diagrams being given in Fig. 20 to 23. The very low values of the modulus of elasticity are in beams having knots. It is seen that the averages are a very little lower than those found for the full-size beams.

Table 24 gives the modulus of elasticity of the small beams of Series M and N calculated from the center deflections.

24. *Effect of Knots and Other Defects.*—Certain statements bearing on the influence of knots upon the strength and manner of failure of timber beams, which are apparent from a study of the general properties of wood, are confirmed by these tests. The presence of small knots along or near the neutral axis, especially toward the ends of the beam, increases the resistance to horizontal shear. Seasoning checks do not form to the same extent nor are they continuous for so great a distance in wood having knots so located, and a shear failure passes around such knots and makes a jagged and irregular break. The presence of larger knots along the middle of the beam, located in such a way that their influence (i. e., with reference to the direction of the grain) does not extend into the lower or upper one-third of the depth of the beam, is not especially injurious. It is important to note, however, that knots located in the lower quarter or upper quarter of the beam and within the portion of the length which has the maximum bending moment, as for example the middle third in beams loaded at the one-third points, decrease the carrying strength of the beam very markedly and constitute a serious defect. The defect has greater influence when the knot carries with it a considerable change of

TABLE 22.

MODULI OF ELASTICITY CALCULATED FROM DEFORMATIONS AND DEFLECTIONS.

The modulus of elasticity was calculated, (1) from the deformation on the compression side, (2) from the deformation on the tension side, (3) from the deflection of the stringer.

Des.	Modulus of Elasticity lb. per sq. in.			Description
	(1) Top Fiber	(2) Bottom Fiber	(3) Deflection	
C 1	1 930 000	1 765 000	1 590 000	Untreated shortleaf pine.
C 2	1 925 000	1 650 000	1 593 000	Untreated shortleaf pine.
C 3	2 130 000	2 400 000	1 595 000	Untreated shortleaf pine.
C 4	2 400 000	1 690 000	1 585 000	Untreated shortleaf pine.
Av.	2 096 000	1 876 000	1 591 000	
C 5	1 580 000	1 650 000	1 221 000	Creosoted shortleaf pine.
C 6	1 650 000	1 600 000	1 325 000	Creosoted shortleaf pine.
C 7	1 250 000	1 060 000	1 045 000	Creosoted shortleaf pine.
C 8	1 640 000	1 770 000	1 350 000	Creosoted shortleaf pine.
C 9	1 740 000	1 390 000	1 225 000	Creosoted shortleaf pine.
C 10	1 740 000	1 535 000	1 300 000	Creosoted shortleaf pine.
C 11	1 065 000	963 000	887 000	Creosoted shortleaf pine.
C 12	1 750 000	1 860 000	1 478 000	Creosoted shortleaf pine.
Av.	1 552 000	1 478 000	1 229 000	
C 13	2 440 000	1 830 000	1 590 000	Untreated loblolly pine.
C 14	2 040 000	1 800 000	1 474 000	Untreated loblolly pine.
C 15	2 200 000	2 020 000	1 645 000	Untreated loblolly pine.
C 16	1 695 000	2 140 000	1 570 000	Untreated loblolly pine.
Av.	2 094 000	1 992 000	1 570 000	
C 17	1 960 000	1 430 000	1 150 000	Creosoted loblolly pine.
C 18	1 900 000	.....	1 060 000	Creosoted loblolly pine.
C 19	1 530 000	1 170 000	1 090 000	Creosoted loblolly pine.
C 20	1 430 000	1 500 000	1 130 000	Creosoted loblolly pine.
C 21	1 260 000	905 000	975 000	Creosoted loblolly pine.
C 22	1 630 000	1 400 000	1 030 000	Creosoted loblolly pine.
C 23	2 265 000	1 725 000	1 132 000	Creosoted loblolly pine.
C 24	1 226 000	1 175 000	1 095 000	Creosoted loblolly pine.
Av.	1 650 000	1 329 000	1 083 000	

direction of grain on either side and above and below it. Beams A 6 and F 7, Plates 1 and 8 are examples of this. Special care should be given in inspection to throw out sticks in which the size and location of knots are such as to impair the strength of the stick, even if such rejection may increase the cost of the materials. It seems to be true that the influence of knots is less when the stick is placed so that the knot comes on the compression side rather than on the tension side, provided, of course, the knot is solid.

Cross grain is a common defect which seriously impairs the strength of timber. The saw marks may hide the grain. Tension

TABLE 23.
MODULUS OF ELASTICITY OF SMALL BEAMS.

Values are given in lb. per sq. in.

Des.	E	Des.	E	Des.	E	Des.	E
Series A. Untreated Longleaf Pine.							
A 1a	1 665 000	A 6a	1 005 000	A 11a	1 546 000	A 16a	1 570 000
A 1b	1 323 000	A 6b	1 422 000	A 11b	1 750 000	A 16b	1 570 000
A 1c	1 593 000	A 6c	1 333 000	A 11c	1 585 000	A 16c	1 715 000
A 1b	1 642 000	A 6d	1 593 000	A 11d	1 568 000	A 16d	1 800 000
A 2a	2 000 000	A 7a	1 690 000	A 12a	1 641 000	A 17a	1 527 000
A 2b	1 740 000	A 7b	1 735 000	A 12b	1 297 000	A 17b	1 353 000
A 2c	1 960 000	A 7c	1 814 000	A 12c	1 700 000	A 17c	1 567 000
A 2d	1 863 000	A 7d	1 863 000	A 12d	1 470 000	A 17d	1 617 000
A 3a	1 520 000	A 8a	1 347 000	A 13a	1 325 000	A 18a	1 502 000
A 3b	1 616 000	A 8b	883 000	A 13b	1 350 000	A 18b	1 690 000
A 3c	1 460 000	A 8c	1 078 000	A 13c	1 519 000	A 18c	1 420 000
A 3d	1 550 000	A 8d	1 347 000	A 13d	2 035 000	A 18d	1 320 000
A 4a	1 445 000	A 9a	564 000	A 14a	1 645 000	A 19a	1 323 000
A 4b	1 347 000	A 9b	1 433 000	A 14b	1 200 000	A 19b	1 125 000
A 4c	1 010 000	A 9c	1 640 000	A 14c	1 200 000	A 19c	663 000
A 4d	981 000	A 9d	1 246 000	A 14d	1 347 000	A 19d	1 078 000
A 5a	1 078 000	A 10a	1 346 000	A 15a	2 056 000	A 20a	1 593 000
A 5b	1 250 000	A 10b	1 005 000	A 15b	2 155 000	A 20b	1 642 000
A 5c	981 000	A 10c	1 423 000	A 15c	1 567 000	A 20c	1 765 000
A 5d	1 152 000	A 10d	1 294 000	A 15d	1 275 000	A 20d	1 690 000
				Av.		.....	1 462 000
Series B. Unseasoned Longleaf Pine.							
B 1b	1 315 000	B 5a	2 060 000	B 8a	1 390 000	B 11b	1 337 000
B 1c	1 170 000	B 5b	2 155 000	B 8b	1 396 000	B 11c	1 723 000
B 2a	1 495 000	B 5c	2 125 000	B 8c	1 565 000	B 11d	1 587 000
B 2b	1 803 000	B 5d	1 867 000	B 8d	1 495 000	B 12a	1 570 000
B 2c	1 386 000	B 6a	1 170 000	B 9a	1 645 000	B 12b	1 390 000
B 2d	1 338 000	B 6b	1 383 000	B 9b	1 705 000	B 12c	1 136 000
B 3a	1 673 000	B 6c	1 705 000	B 9c	1 720 000	B 12d	1 095 000
B 3b	1 433 000	B 6d	1 703 000	B 9d	1 685 000	B 13a	1 338 000
B 3c	1 553 000	B 7a	1 575 000	B 10a	1 540 000	B 13b	1 465 000
B 3d	1 515 000	B 7b	1 450 000	B 10b	1 643 000	B 13c	1 460 000
B 4a	1 895 000	B 7c	1 402 000	B 10c	1 848 000	B 13d	1 617 000
B 4b	2 015 000	B 7d	1 415 000	B 10d	1 630 000	B 14a	1 182 000
B 4c	1 990 000			B 11a	1 385 000	B 14b	1 375 000
				Av.		.....	1 558 000
Series D. Creosoted Loblolly Pine.							
D 16a	443 000	D 20a	1 152 500	D 22a	1 495 000	D 24c	1 380 000
D 16d	100 000	D 20b	1 225 000	D 22b	1 643 000	D 24d	1 510 000
D 17a	760 000	D 20c	1 178 000	D 22c	1 593 000	D 25a	1 193 000
D 18a	907 500	D 20d	1 120 000	D 22d	1 567 000	D 25b	1 163 000
D 18c	1 177 000	D 21a	1 030 000	D 23a	1 665 000	D 25c	905 000
D 19a	1 795 000	D 21b	1 380 000	D 23b	1 700 000	D 25d	807 000
D 19b	1 488 000	D 21c	1 303 000	D 23c	1 542 000	D 26a	1 145 000
D 19c	1 120 000	D 21d	1 355 000	D 23d	1 457 000	D 26b	1 505 000
D 19d	1 175 000			D 24a	1 430 000	D 26c	1 225 000
				D 24b	1 565 000	D 26d	1 470 000
				Av.		.....	1 260 000

TABLE 23 (Concluded)
MODULUS OF ELASTICITY OF SMALL BEAMS

Des.	E	Des.	E	Des.	E	Des.	E
Series D. Untreated Loblolly Pine							
D 1a	1 570 000	D 4a	1 660 000	D 8c	865 000	D 11d	896 000
D 1b	1 340 000	D 4b	1 695 000	D 8d	1 120 000	D 12a	1 225 000
D 1c	1 487 000	D 4c	1 512 000	D 9a	1 396 000	D 12b	1 330 000
D 1d	1 420 000	D 4d	1 405 000	D 9b	1 418 000	D 12c	969 000
D 2a	1 330 000	D 6a	920 000	D 9c	1 280 000	D 12d	1 016 000
D 2b	1 383 000	D 6b	766 000	D 9d	1 112 000	D 13a	1 215 000
D 2c	527 500	D 6c	975 000	D 10a	1 725 000	D 13b	1 150 000
D 2d	1 290 000	D 6d	1 110 000	D 10b	1 185 000	D 13c	1 276 000
D 3b	1 143 000	D 7b	1 720 000	D 10c	1 156 000	D 13d	1 452 000
D 3c	902 500	D 7c	1 153 000	D 10d	1 385 000	D 14a	1 373 000
D 3d	885 000	D 7d	1 600 000	D 11a	1 293 000	D 14b	972 500
		D 8a	997 500	D 11b	1 228 000	D 14c	1 460 000
		D 8b	1 050 000	D 11c	905 000	D 14d	1 465 000
				Av.		.....	1 243 000

Series E. Old Douglas Fir

E 1a	1 897 000	E 4a	1 718 000	E 7a	2 030 000	E 10a	1 610 000
E 1b	1 875 000	E 4b	1 862 000	E 7b	1 875 000	E 10b	817 000
E 1c	1 883 000	E 4c	1 640 000	E 7c	1 563 000	E 11c	1 408 000
E 1d	1 850 000	E 4d	1 845 000	E 7d	1 665 000	E 10d	1 616 000
E 2a	1 850 000	E 5a	1 380 000	E 8a	1 960 000	E 11a	1 490 000
E 2b	2 070 000	E 5b	1 534 000	E 8b	859 000	E 11b	1 618 000
E 2c	1 730 000	E 5c	1 815 000	E 8c	1 650 000	E 11c	1 103 000
E 2d	2 040 000	E 5d	1 800 000	E 8d	1 564 000	E 11d	1 820 000
E 3a	1 765 000	E 6a	1 485 000	E 9a	1 350 000	E 12a	1 448 000
E 3b	1 715 000	E 6c	1 617 000	E 9b	1 442 000	E 12b	1 708 000
E 3c	1 667 000	E 6d	1 690 000	E 9c	1 442 000	E 12c	1 393 000
E 3d	1 650 000			E 9d	1 665 000	E 12d	1 446 000
				Av.		.....	1 635 000

Series F. New Douglas Fir

F 1a	1 195 000	F 4a	1 717 000	F 11a	1 720 000	F 14a	1 250 000
F 1b	1 340 000	F 4b	1 557 000	F 11b	1 505 000	F 14b	1 250 000
F 1c	983 000	F 4c	1 443 000	F 11c	1 755 000	F 14c	1 330 000
F 2a	1 127 000	F 4d	1 470 000	F 11d	1 533 000	F 14d	1 176 000
F 2b	1 010 000	F 9a	1 675 000	F 12a	1 432 000	F 15a	1 485 000
F 2c	882 000	F 9b	1 282 000	F 12b	1 237 000	F 15b	1 406 000
F 2d	1 147 000	F 9c	1 673 000	F 12c	1 567 000	F 15c	1 510 000
F 3a	1 825 000	F 10a	1 765 000	F 12d	1 382 000	F 15d	1 225 000
F 3b	1 366 000	F 10b	1 765 000	F 13a	1 306 000	F 16a	1 562 000
F 3c	1 345 000	F 10c	1 680 000	F 13b	1 487 000	F 16b	1 730 000
F 3d	1 513 000	F 10d	1 176 000	F 13c	1 328 000	F 16c	1 363 000
				F 13d	1 276 000	F 16d	1 250 000
				Av.		.....	1 413 000

TABLE 24.

MODULUS OF ELASTICITY OF SMALL BEAMS, SERIES M AND N.

Des.	E	Des.	E	Des.	E	Des.	E
Series M. Creosoted Loblolly Pine.							
M1a1	1 258 000	M2a1	1 565 000	M3a1	1 128 000	M4a1	1 440 000
M1a1	1 065 000	M2a1	1 476 000	M3a1	1 075 000	M4a1	1 445 000
M1a2	1 470 000	M2a2	1 075 000	M3a2	1 120 000	M4a2	1 470 000
M1a2	1 260 000	M2a2	1 188 000	M3a2	1 070 000	M4a2	1 560 000
M1a3	1 190 000	M2a3	1 275 000	M3a3	1 058 000	M4a3	1 387 000
M1a3	1 295 000	M2a3	982 000	M3a3	932 000	M4a3	1 607 000
M1a4	1 225 000	M2a4	1 213 000	M3a4	884 000	M4a4	1 540 000
M1a4	1 187 000	M2a4	1 214 000	M3a4	1 262 000	M4a4	1 415 000
M1c1	1 082 000	M2c1	1 110 000	M3c1	1 128 000	M4c1	1 466 000
M1c1	1 225 000	M2c1	1 176 000	M3c1	987 000	M4c1	1 470 000
M1c2	1 066 000	M2c2	1 388 000	M3c2	1 320 000	M4c2	1 372 000
M1c2	1 225 000	M2c2	1 437 000	M3c2	1 248 000	M4c2	1 316 000
M1c3	1 340 000	M2c3	1 392 000	M3c3	1 314 000	M4c3	1 538 000
M1c3	1 115 000	M2c3	1 223 000	M3c3	1 303 000	M4c3	1 715 000
M1c4	1 110 000	M2c4	1 445 000	M3c4	1 200 000	M4c4	1 715 000
M1c4	1 052 000	M2c4	1 017 000	M3c4	1 190 000	M4c4	1 568 000
Av.....							1 275 000
Series N. Loblolly Pine.							
Untreated				Creosoted			
N1c1	752 000	N3c3	1 225 000	N1c2	747 500	N3c2	1 305 000
N1c1	632 500	N3c3	1 188 000	N1c2	784 500	N3c2	1 268 000
N1c3	907 000	N3a1	1 304 000	N1c4	794 000	N3c4	1 323 000
N1c3	858 000	N3a1	1 213 000	N1c4	872 500	N3c4	1 297 000
N1a1	735 000	N3a3	1 495 000	N1a2	736 000	N3a2	1 260 000
N1a1	807 500	N3a3	1 530 000	N1a2	736 000	N3a2	1 304 000
N1a3	1 055 000	N4c1	735 000	N1a4	849 000	N3a4	1 043 000
N1a3	796 000	N4c1	925 000	N1a4	566 000	N3a4	1 133 000
N2c3	1 212 000	N4a3	1 380 000	N2c2	1 223 000	N4c2	693 000
N2c3	1 223 000	N4a3	1 415 000	N2c2	1 460 000	N4c2	1 020 000
N2a1	1 568 000			N2c4	1 200 000	N4c4	1 130 000
N2a1	1 653 000			N2c4	1 040 000	N4c4	739 000
N2a3	1 233 000			N2a2	1 500 000	N4a2	1 270 000
N2a3	1 345 000			N2a2	1 470 000	N4a2	1 333 000
N3c1	1 570 000			N2a4	1 382 000	N4a4	1 165 000
N3c1	1 300 000			N2a4	1 076 000	N4a4	1 178 000
Av.....			1 161 000	Av.....			1 091 000

breaks at low loads in full-size sticks may frequently be traced to cross grain.

Shakes and seasoning checks are deleterious to horizontal shearing strength. A shake in the lower or upper portion may cause failure in tension or compression or a combination of one of these with shear failure. The liability of a wood to check during the time of seasoning has then an important bearing upon its desirability.

That knots and cross grain contributed largely to the weakness of the timber is seen in looking over the results, although it should be noted that in most of the stringers the defects were not such as to have caused rejection under ordinary inspection. In Series A, nearly every piece which failed in tension had knots and cross grain. A 6 and A 10 (Plates 1 and 2) are good examples, particularly of the low strength which may result from such defects. The stringer A 6 had been selected as an example of knots which were plain cause for rejection. In Series C four sticks failing in tension gave low values, due to knots and cross grain. In Series D, six sticks showing bad knots and cross grain failed in tension. In the same way the fir stringers failing by tension at low loads contained knots and showed cross grain. All of these, however, would be called good sticks. A 4 is an example of a defect of another kind causing tension failure, in this case a hidden defect, as the shake was not visible externally. The seasoning check in A 1 along which it failed by horizontal shear at a very low load was conspicuous; but horizontal shear did not always occur along seasoning checks which seemed the most important, and some sticks, as B 11, which were fairly free from seasoning checks, failed by horizontal shear. C 9 and D 14 are examples of cross grain affecting the horizontal shearing strength. A study of the views given in the Plates 1 to 16 will indicate something of the size and position of defects.

25. *Relation of Depth to Length.*—It is evident that for stated values of the modulus of rupture and of the longitudinal shearing stress in a beam, a ratio of length of span to depth of stringer will exist for which the stringer is as likely to fail in cross bending as in horizontal shear. Thus, for a modulus of rupture of 5000 lb. per sq. in. and a horizontal shearing stress of 300 lb. per sq. in., using one-third point loading, a span twelve and one-half times its depth will give the two stresses simultaneously. This makes a depth of 13 in. for a span of $13\frac{1}{2}$ ft. If instead of the modulus of rupture the elastic limit be used, say, 3000 lb. per sq. in., and if for the elastic limit or yield point of the horizontal shearing strength 300 lb. per sq. in. be taken, the resulting ratio is $7\frac{1}{2}$. This would correspond to a depth of 21.6 in. for a span of $13\frac{1}{2}$ ft. For the first-named values, the carrying strengths of beams of depths greater than 13 in. would increase only as the depth of beam; for the latter, depths less than 21.6 in. would not fail in

horizontal shear before the elastic limit of the material was reached. It may be well to find whether the tests bear out such reasoning and whether other conditions may not cover up the influence of such a comparison.

In Table 8 are given values for longleaf pine for depths of 12, 14 and 16 inches. It is plain that the small number of test pieces and the variation in results will not permit conclusions to be drawn. Some of the groups contained more poor sticks than others. The abnormally high values found in A 11, A 12, and A 13 help to make comparison difficult. Evidently the data are insufficient to show whether the horizontal shearing strengths will be alike for stringers of different depths. Uniformity in selection is difficult, and it is likely that any variation in the strength found in even a long series would be masked by differences in the selection of the piece and the method of seasoning.

It must be remembered that additional depth gives additional stiffness and smaller deflections at the same fiber stress and that stiffness is an important element in bridge stringers. Even if horizontal shear controlled the strength in a given depth of stringer, greater depth may be accepted as an additional safeguard against failure at relatively low loads by reason of knots and similar defects which may have passed by unnoticed, and it will be seen that the tests include a number of stringers which failed in cross bending at unexpectedly low loads. It seems to be the case that unnoticed defects which seriously affect cross-bending tensile strength are more frequent than are the defects which give low shearing strength. If the ultimate horizontal shearing strength of timber is but little higher than the yield point in horizontal shear, as seems to be the case, it would seem reasonable to use a relatively higher working stress in shear than in fiber stress, or in other words, to make a lower factor of safety for horizontal shear than for fiber stress. This, in effect, agrees with current usage.

26. *Effect of Seasoning and of Creosoting.*—The tests may not be expected to throw light upon the effect of seasoning on the strength and stiffness of timber. The presence of knots and cross grain in a few sticks in one series, even minor variations in the quality of the wood, may easily neutralize the effect of differences in moisture. Series A and B give no marked differences in either strength or stiffness. The principal difference in results

in Series E and F is in stiffness, but the higher modulus of elasticity in the long-seasoned timber may be due in part to differences in wood. The effect of seasoning upon resistance to horizontal shear through the development of seasoning checks is important, and it is apparent that even in the earlier stages of seasoning (as shown in Series B) the formation of seasoning checks produces a marked weakening effect and must be taken into account in estimating the strength of large size timber. It may be expected that for such timber the differences in strength and stiffness of partly-seasoned timber and well-seasoned timber will be less than the differences due to variations in quality, except that the increase in seasoning checks is likely to reduce the resistance to horizontal shear.

It has been thought that the creosoting preservation process weakens timber through the action of the high temperature in the preliminary steaming process and through the presence of the oil in the walls of the cells of the wood. The opinion was once advanced that the oil had the effect of the same amount of moisture, but this seems not to have been verified. It has been shown, however, that long exposure to steam at high pressures and high temperatures is detrimental. It would seem, too, that the injection of oil will retard further seasoning and thus preclude the gain in strength which would come with time. It must be expected that differences in test pieces due to knots, cross grain, and quality of the wood may exercise a greater influence than does the process of creosoting.

It will be seen that in the shortleaf pine stringers of Series C the creosoted sticks average 22% less in elastic limit, 17% less in maximum strength, and 23% less in stiffness than do the untreated sticks. In the loblolly pine stringers of the same series, the creosoted sticks average 44% less in elastic limit, 30% less in maximum strength, and 31% less in stiffness. However, in the loblolly pine stringers of Series D the creosoted sticks show the greater strength and there is little difference in the average stiffness. The greater freedom from defects found in the creosoted stringers of Series D as compared with the defects found in the untreated stringers will account for at least a part of this seeming discrepancy.

The test pieces of Series N seem to offer good conditions for comparison. Of the pieces into which the four stringers were

cut, every other piece was creosoted and the remainder were left in the natural state. The untreated test pieces had nine months longer in which to season, which probably offset any advantage which the creosoted sticks may have received in the steaming process. Two pieces in the creosoted lot had bad knots. The creosoted test beams averaged 16% lower in elastic limit, 22% lower in maximum fiber strength, and 6% lower in stiffness than did the untreated test beams. The creosoted shear blocks averaged 8% less than the untreated shear blocks.

As a whole, then, the tests go to corroborate the view that the creosoting preservative process of the ordinary practice decreases the strength and stiffness of beams; but the tests do not throw light on the cause of the difference. Attention may be called to the low resistance to compression at right angles to the grain (bearing strength) which was found in some of the creosoted loblolly stringers.

27. *Properties of the Different Woods.*—It will be noted that for the untreated stringers the range of averages for elastic limit, fiber stress, and shearing stress developed in the several woods is small if we except Series D which seems to have had a large proportion of defective sticks. Omitting Series D, the range of the averages is from 3823, 4420, and 300 lb. per sq. in. for elastic limit, fiber stress and shearing stress, respectively, in the old Douglas fir to 4336, 5430, and 354 lb. per sq. in. in the longleaf pine. The high fiber stress shown in the small test beams cut from the longleaf pine and old Douglas fir stringers is ineffective by reason of low shearing strength and the influence of defects. The low shearing strength is due largely to the presence of large seasoning checks. The longleaf pine showed the greatest effect of seasoning checks, but the shearing strength of the old Douglas fir was much lower. The loblolly pine makes a better showing than might be expected from the general softness and brashness of its wood, and this is due to a relatively high shearing strength. The loblolly pine is less stiff than the other woods. Of course, durability is not here taken into consideration. It would be interesting to know where the elastic limit in horizontal shear lies in these woods, particularly in those having large seasoning checks.

28. *General Comments.*—The ground covered by these tests is so great and the information obtained so varied that no attempt will be made to give a summary of the results. Conclusions have

been stated throughout the discussion. However, it seems proper that at the risk of repetition the following statements be given here.

1. The preponderance of failures in horizontal shear is very marked in every series of tests. The results emphasize the importance of the shearing resistance of the wood in beams of the dimensions of those tested. The cross-breaking failures were in sticks having bad knots and cross grain. A few of these defective sticks would not be called merchantable timber, but many of them might pass inspection as it is usually made. The influence of defects is very marked. Knots, cross grain, and seasoning checks act to give low strength. Any tendency to relax requirements and inspection should be avoided, unless accompanied with the use of lower working stresses.

2. The horizontal shearing resistance developed in the stringers is low in every series of tests. The averages range from 300 to 390 lb. per sq. in., and in individual cases the stress is as low as 200 lb. per sq. in. Comparatively little difference in shearing resistance is found for the different kinds and conditions of wood, for in the clear sticks of the stronger woods large seasoning checks act to prevent the utilization of the full cross-breaking strength of the timber.

3. For the cross-breaking failures the fiber stress developed was also generally low, averaging for the untreated timber from 3690 lb. per sq. in. in the old Douglas fir to 5300 lb. per sq. in. in the longleaf pine. One longleaf pine stringer developed a fiber stress of 8410 lb. per sq. in., and a value as low as 2530 lb. per sq. in. was found.

4. The elastic limit of the beams is seriously affected by defects like knots and cross grain. However, in general, the fiber stress at the elastic limit is proportionally high, the ratio to the fiber stress at failure averaging from 0.67 to 0.90 for the several series of tests.

5. The strength developed in the small test beams cut from the top and bottom of the stringers averages from 50% to 100% higher than that obtained in the stringers, and the results show the futility of taking tests of small sticks as a criterion of the strength of full-size structural timber. The shearing strength developed in the stringers was 60% to 100% of the shearing strength developed in shear blocks cut from the uninjured end of

the stringers at mid-depth and having their full thickness; but these strengths of the shear blocks are much less than will be obtained on small pieces of selected timber.

6. In woods which develop large checks and cracks in seasoning, care should be given to avoid rapid and uneven seasoning in large sticks. Seasoning checks should be recognized as a common source of weakness.

7. The tests of creosoted sticks are insufficient to warrant drawing conclusions. They seem to corroborate the view that timber treated by the creosoting process as usually operated has somewhat less strength and stiffness than untreated timber. The stopping of further seasoning in the creosoted wood is an element which should be considered in such a comparison.

8. The fact that sticks having knots and cross grain are generally less stiff than clear sticks results in the weaker stick taking less than its share of load and the stronger and stiffer stick taking more than its share when defective and clear sticks are placed side by side and are loaded so as to have the same deflection. It is evident that stringers having defects may not receive their calculated proportion of the load. It is interesting to note that the modulus of elasticity calculated from deflections is less than the values derived from the observed deformations of the outer fibers.

9. It is evident that the defects found in structural timber have a strong influence on strength and that rigid inspection should be given.

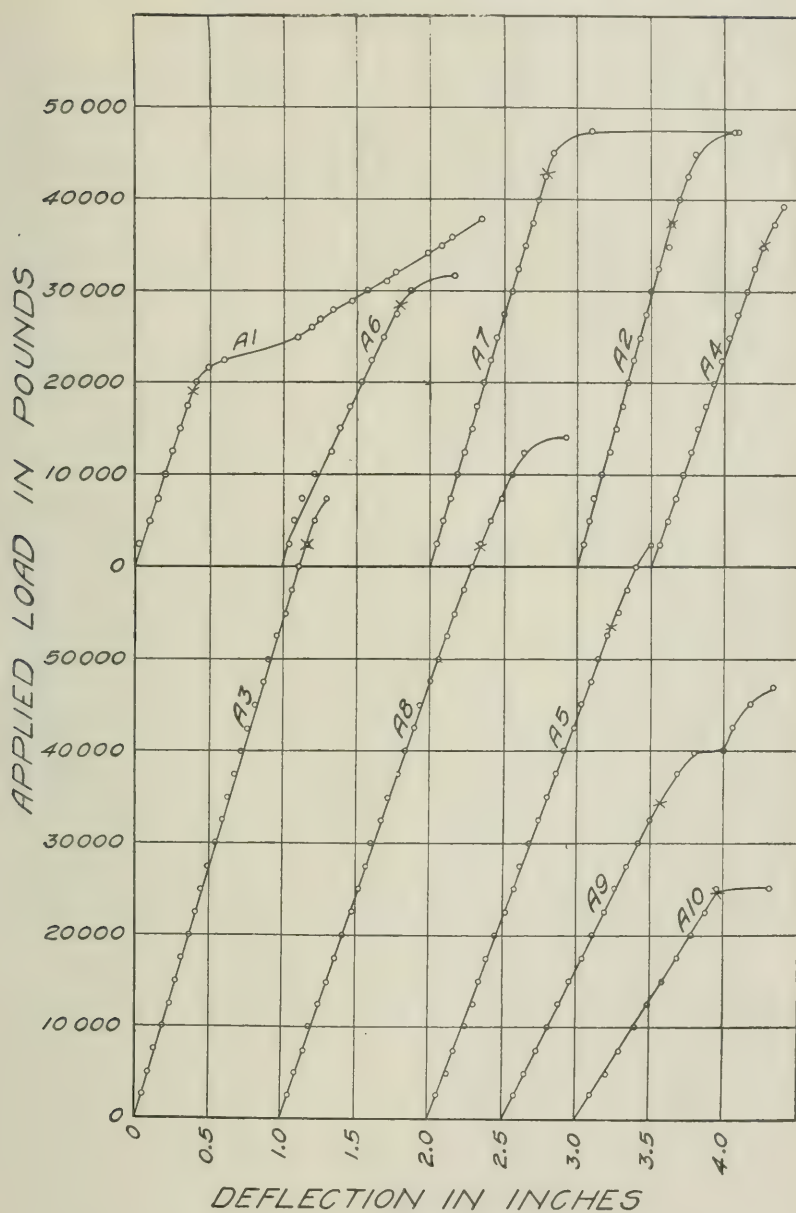


Fig. 11. LOAD-DEFLECTION DIAGRAMS FOR LARGE BEAMS.

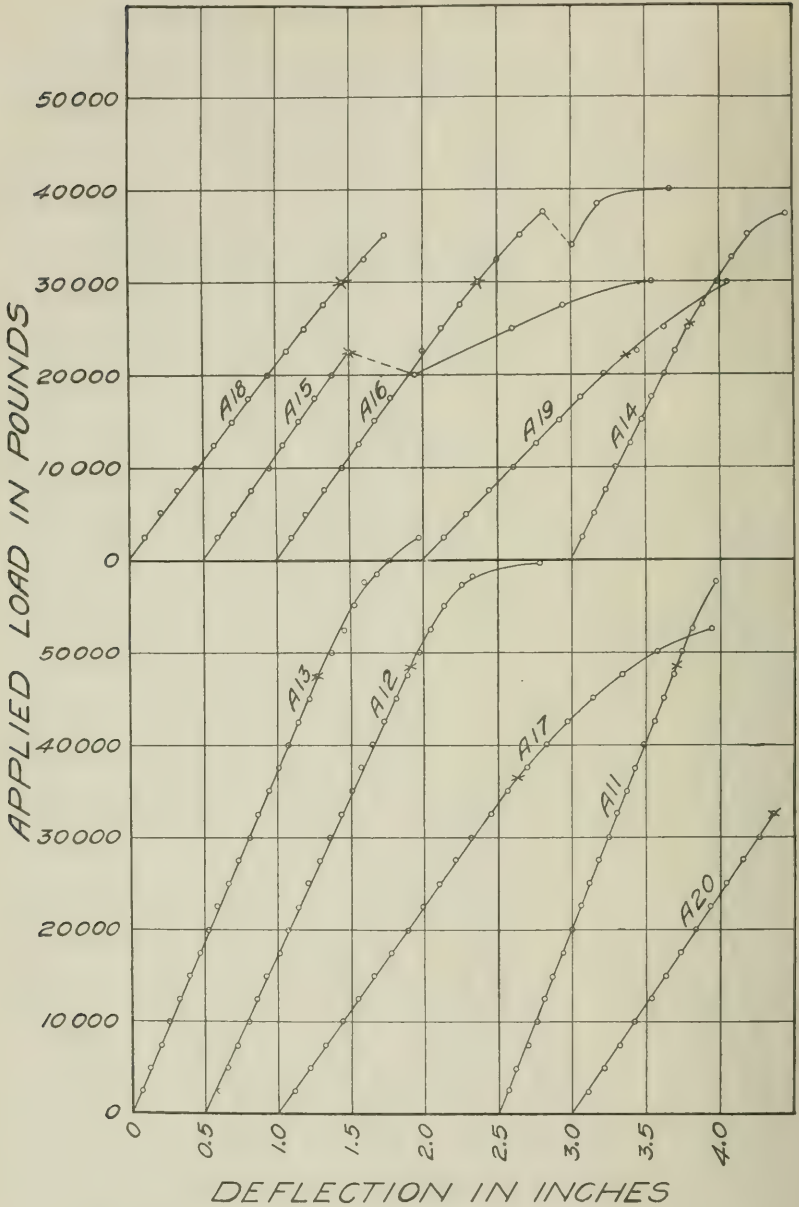


FIG. 12. LOAD-DEFLECTION DIAGRAMS FOR LARGE BEAMS.

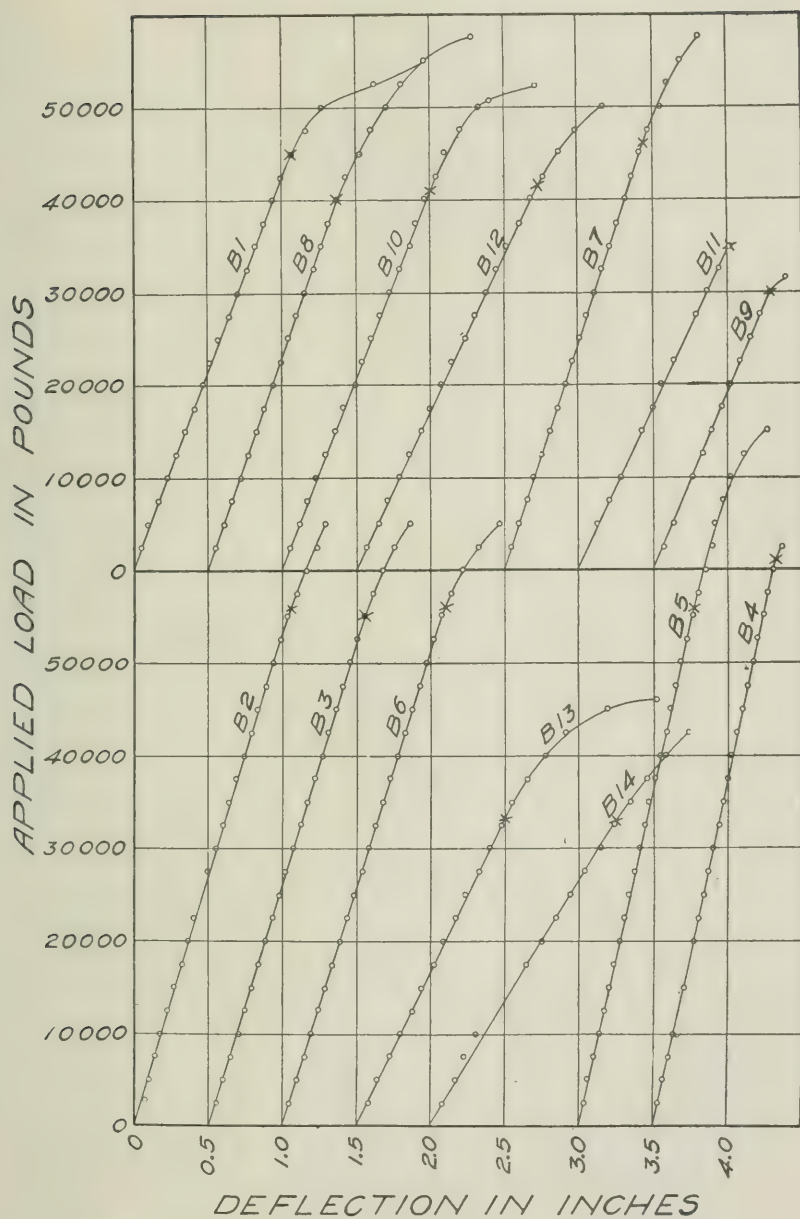


FIG. 13. LOAD-DEFLECTION DIAGRAMS FOR LARGE BEAMS.

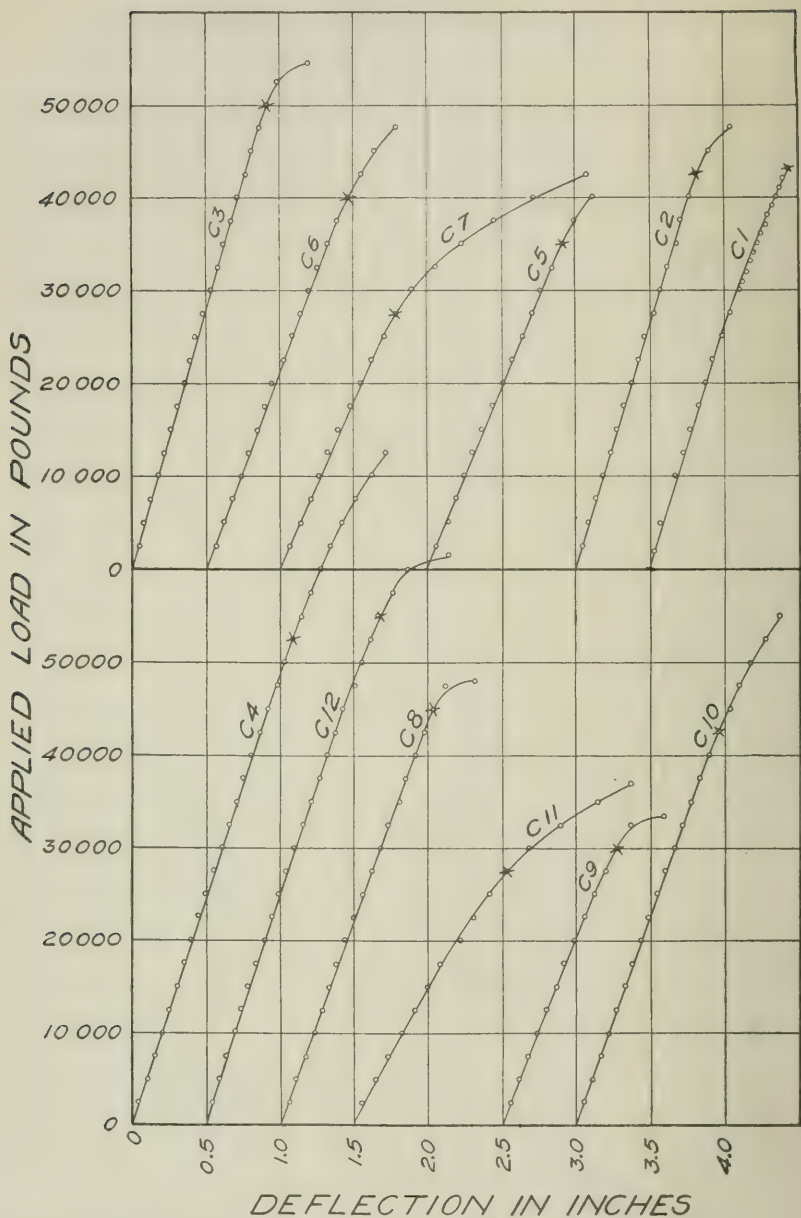


FIG. 14. LOAD-DEFLECTION DIAGRAMS FOR LARGE BEAMS.

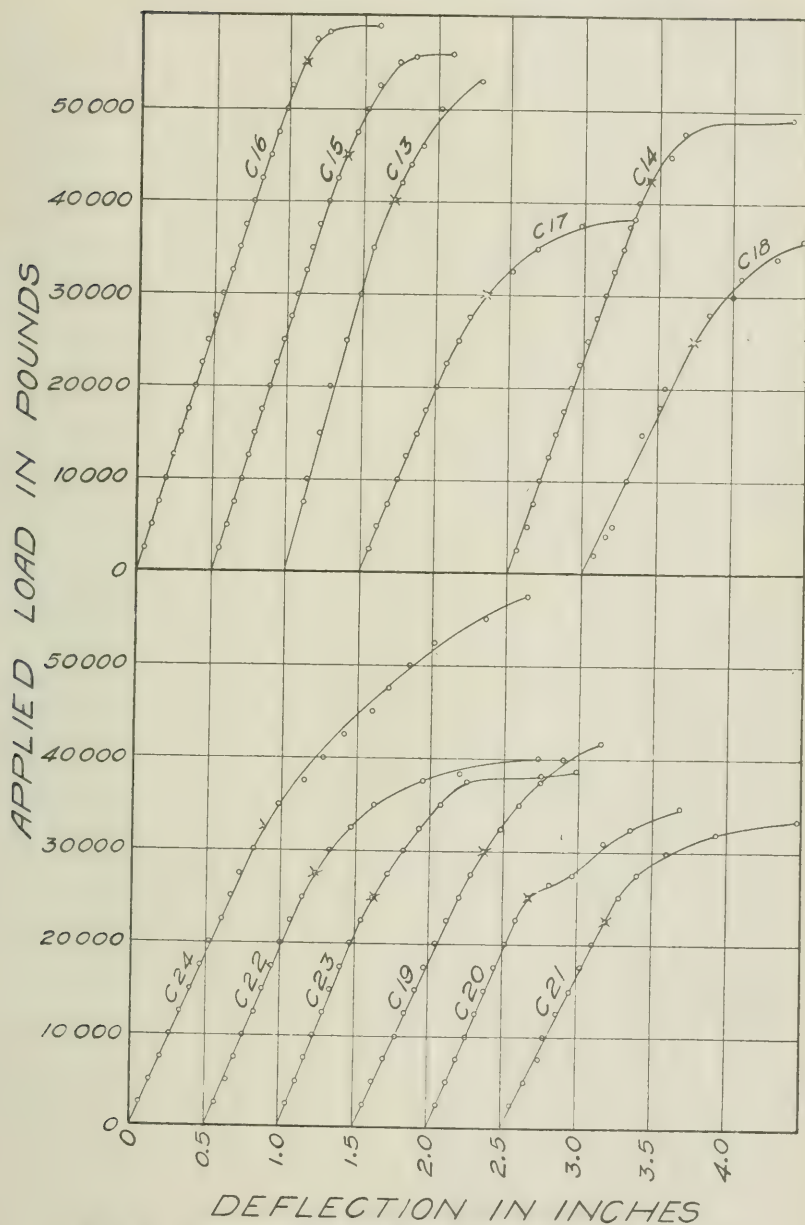


FIG. 15. LOAD-DEFLECTION DIAGRAMS FOR LARGE BEAMS.

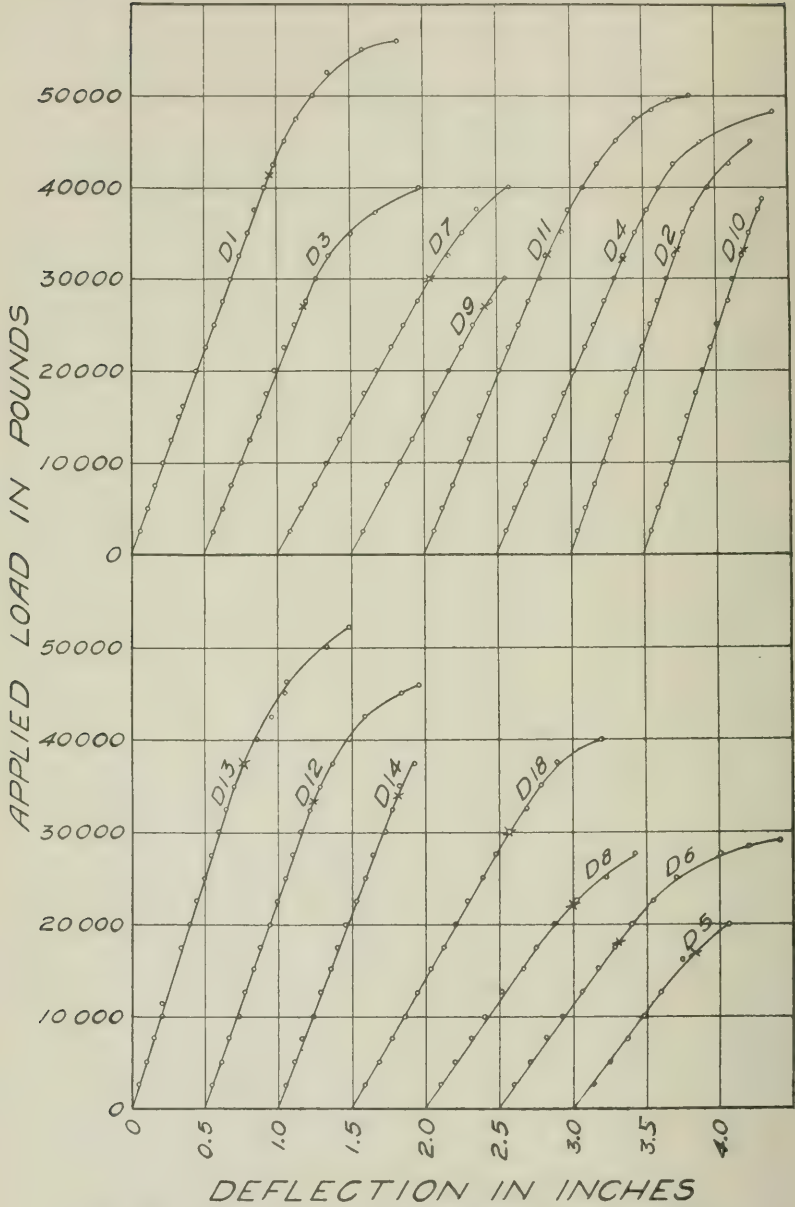


FIG. 16. LOAD-DEFLECTION DIAGRAMS FOR LARGE BEAMS.

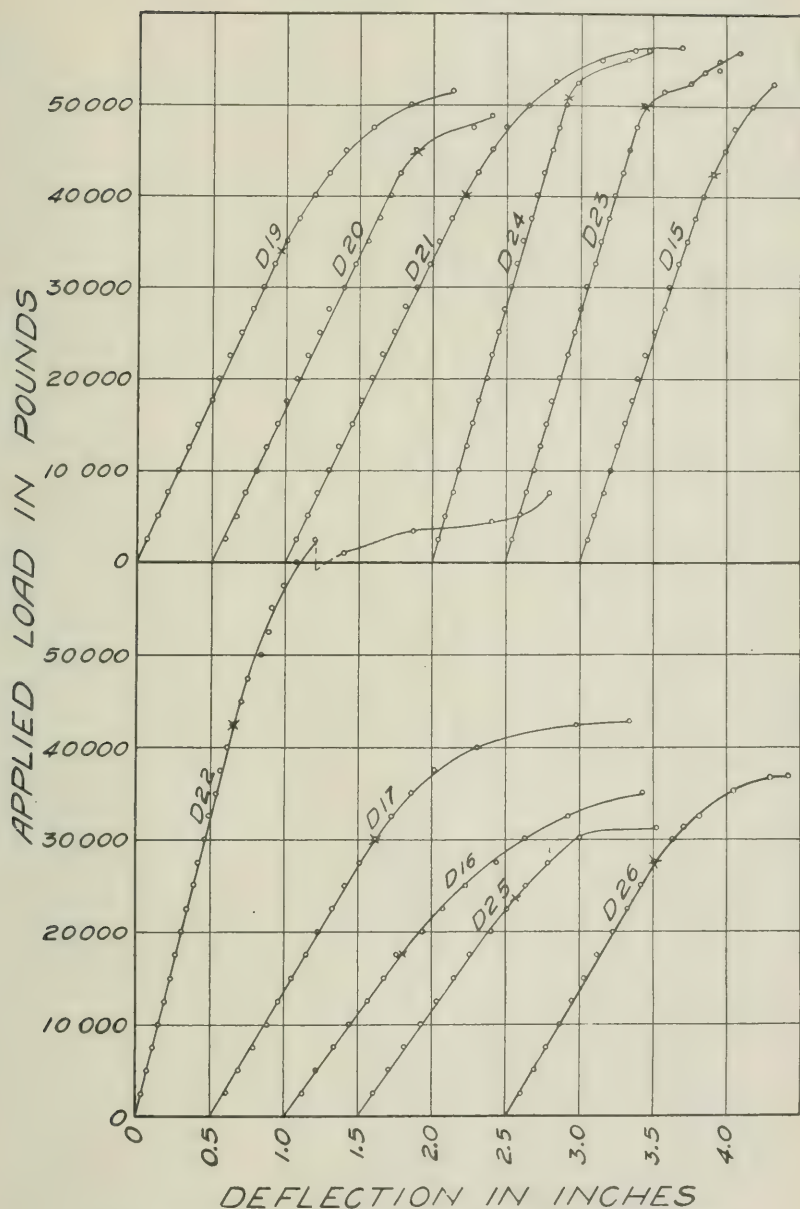


FIG. 17. LOAD-DEFLECTION DIAGRAMS FOR LARGE BEAMS.

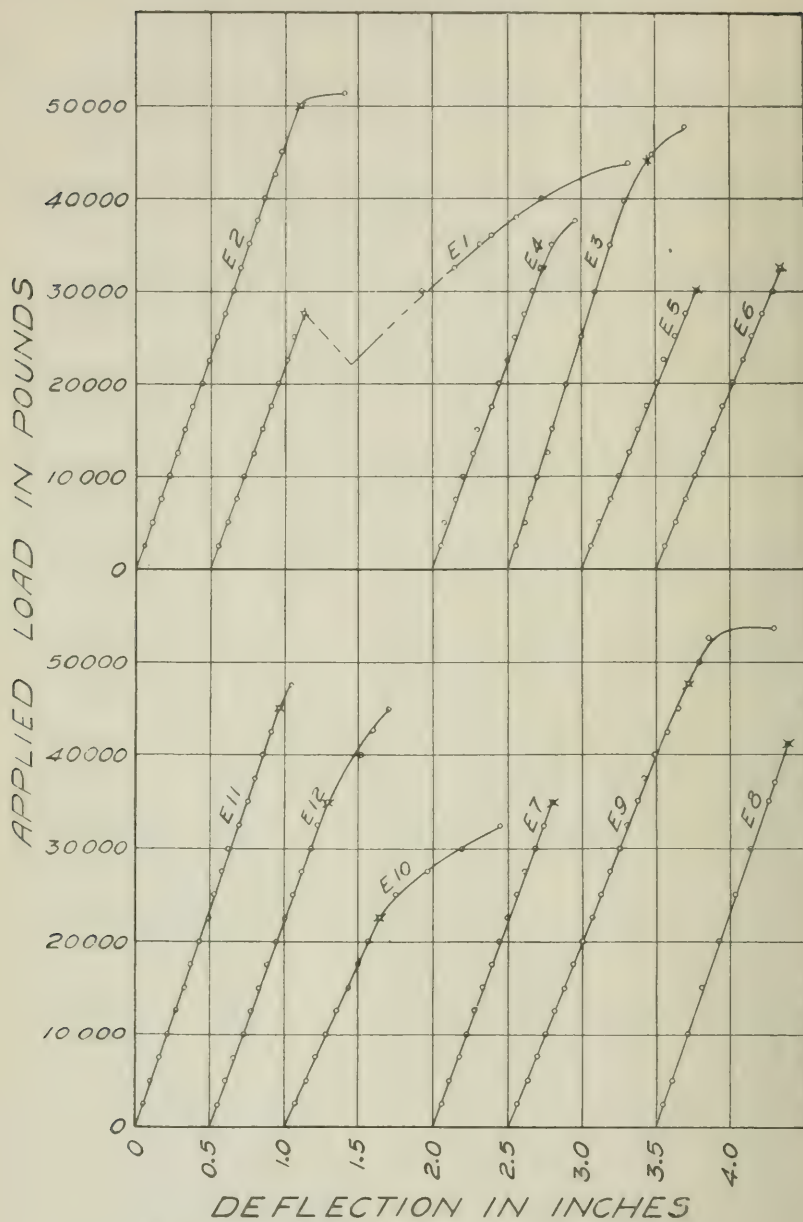


FIG. 18. LOAD-DEFLECTION DIAGRAMS FOR LARGE BEAMS.

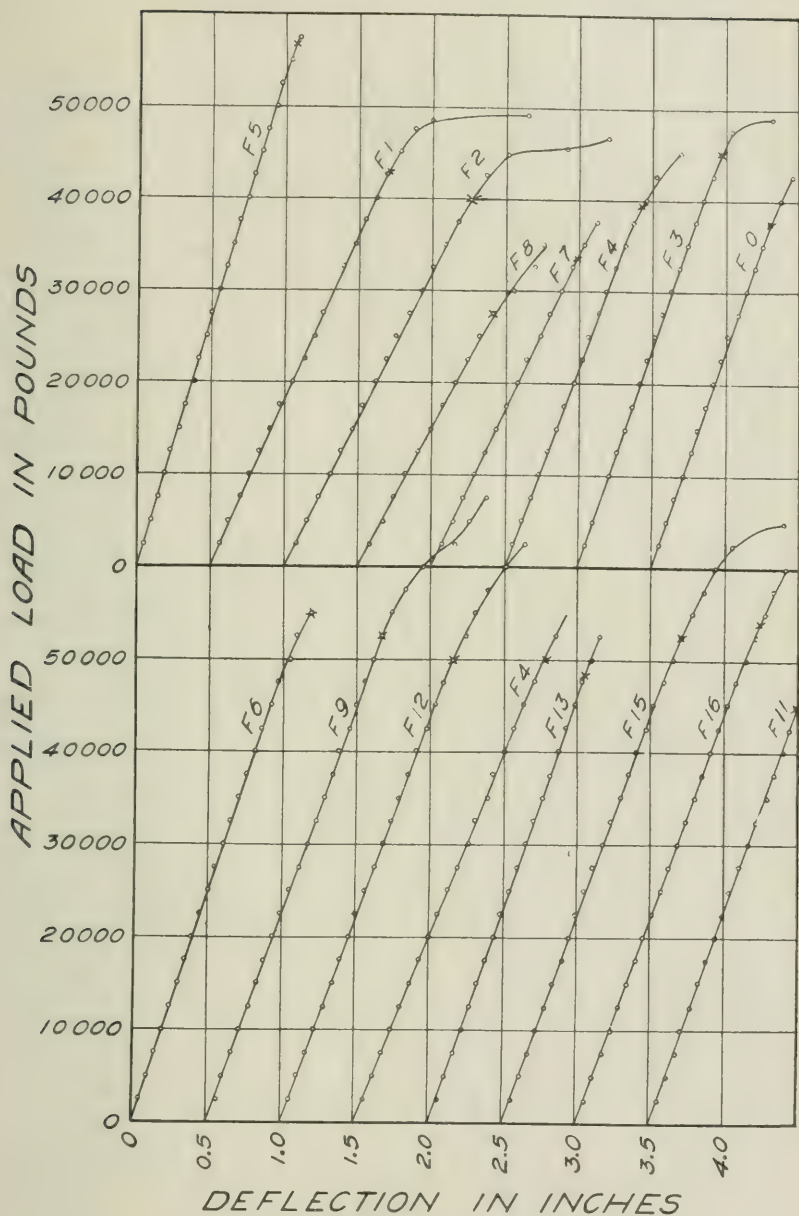


FIG. 19. LOAD-DEFLECTION DIAGRAMS FOR LARGE BEAMS.

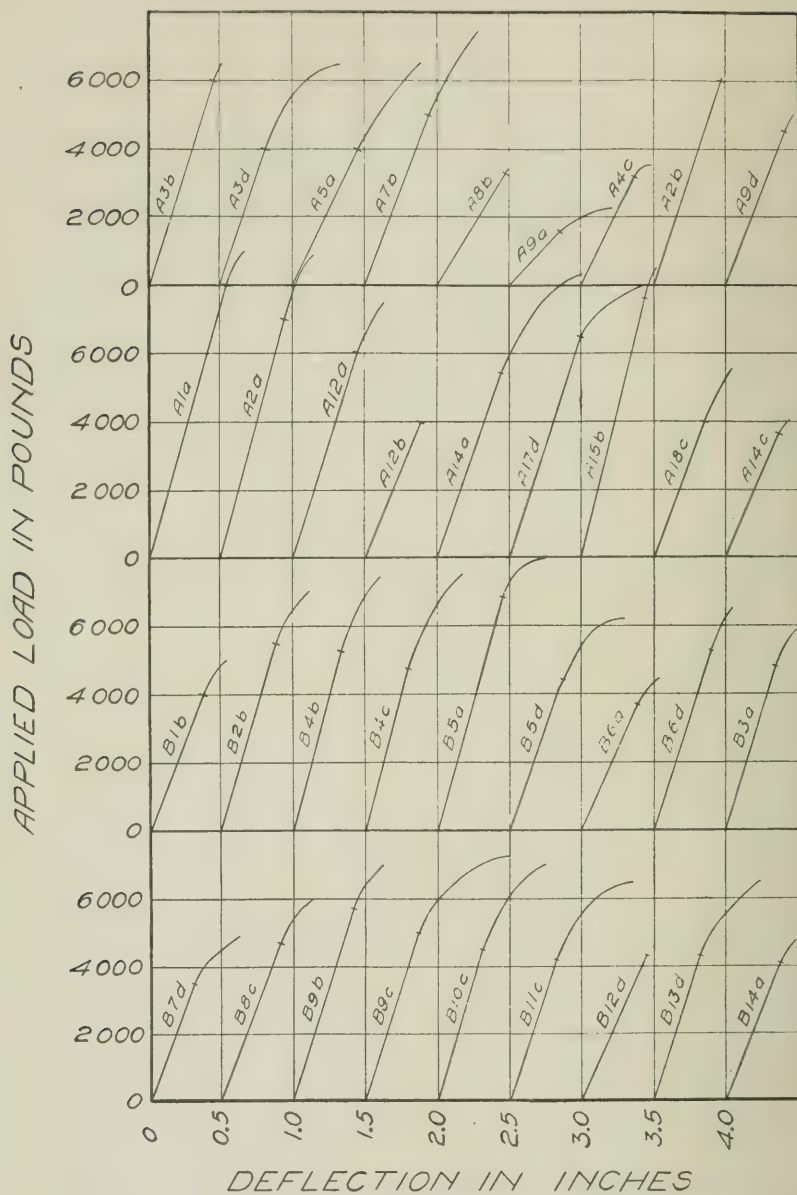


FIG 20. LOAD-DEFLECTION DIAGRAMS FOR SMALL TEST BEAMS.

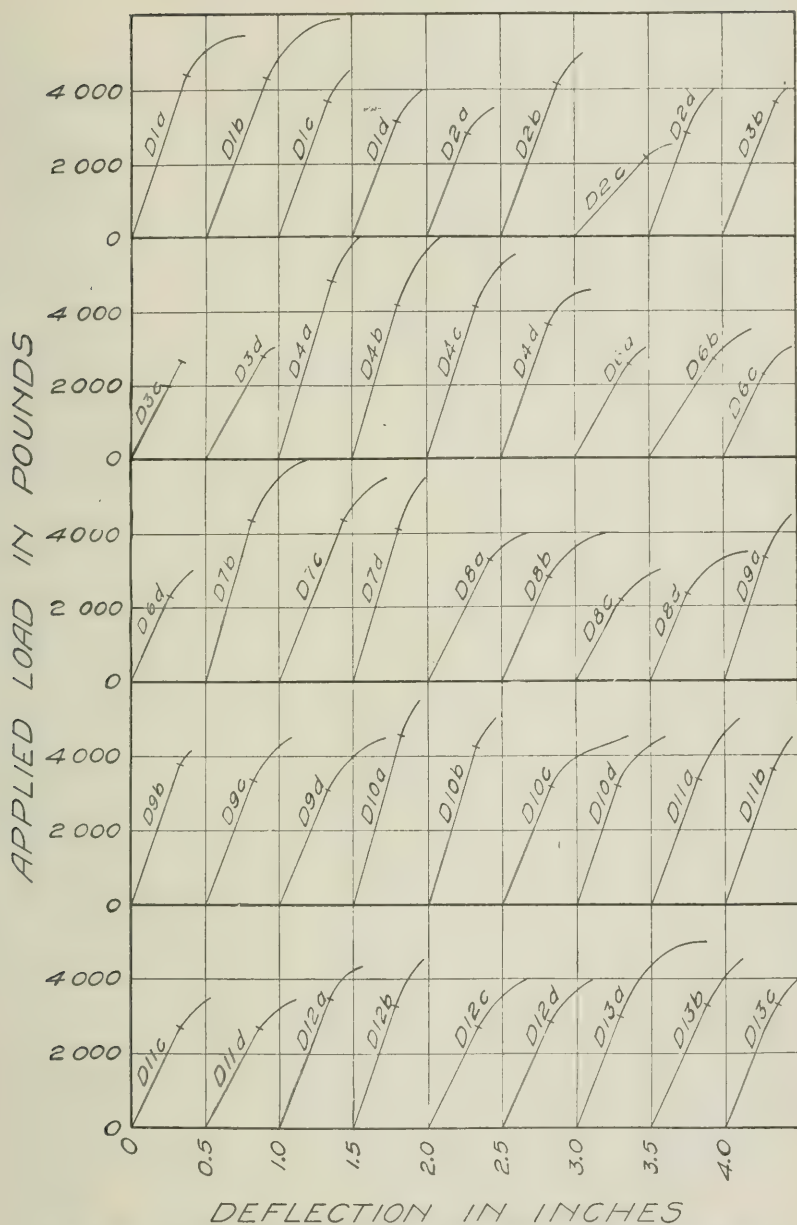


FIG. 21. LOAD-DEFLECTION DIAGRAMS FOR SMALL TEST BEAMS.

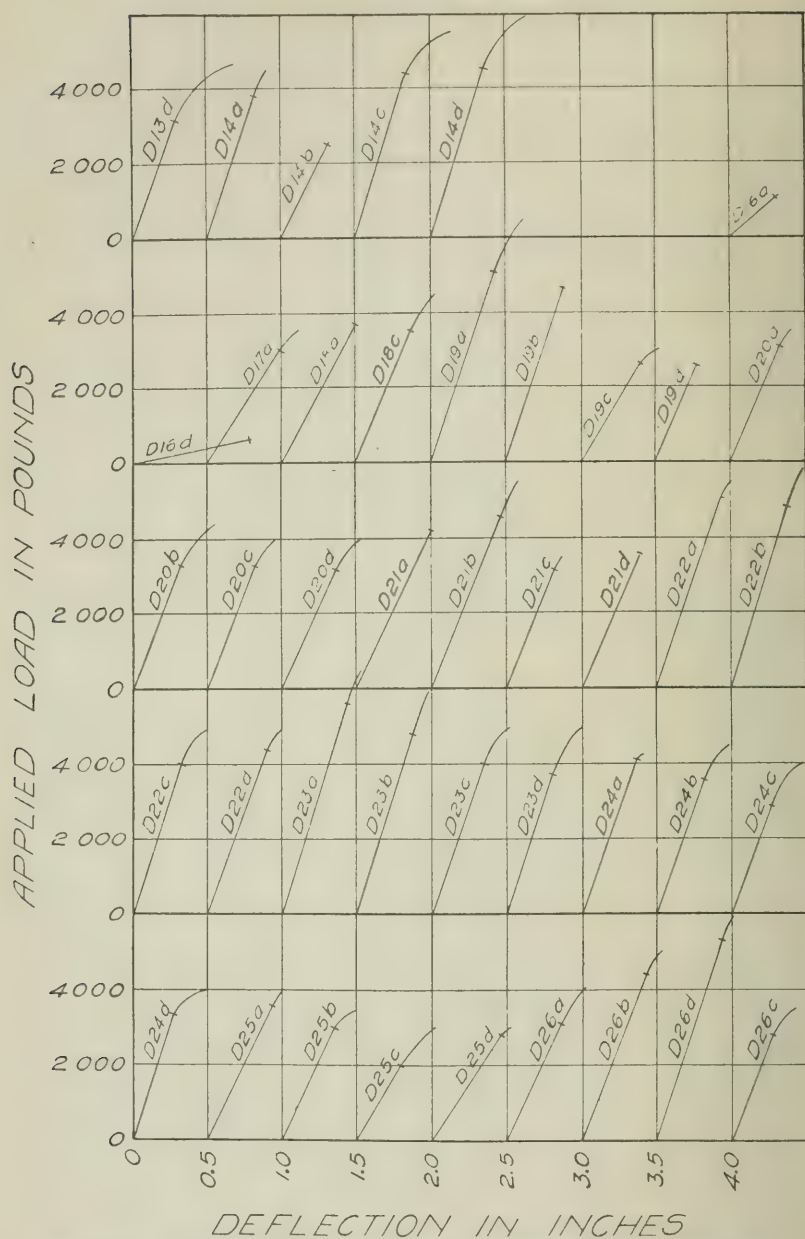


FIG. 22. LOAD-DEFLECTION DIAGRAMS FOR SMALL TEST BEAMS.

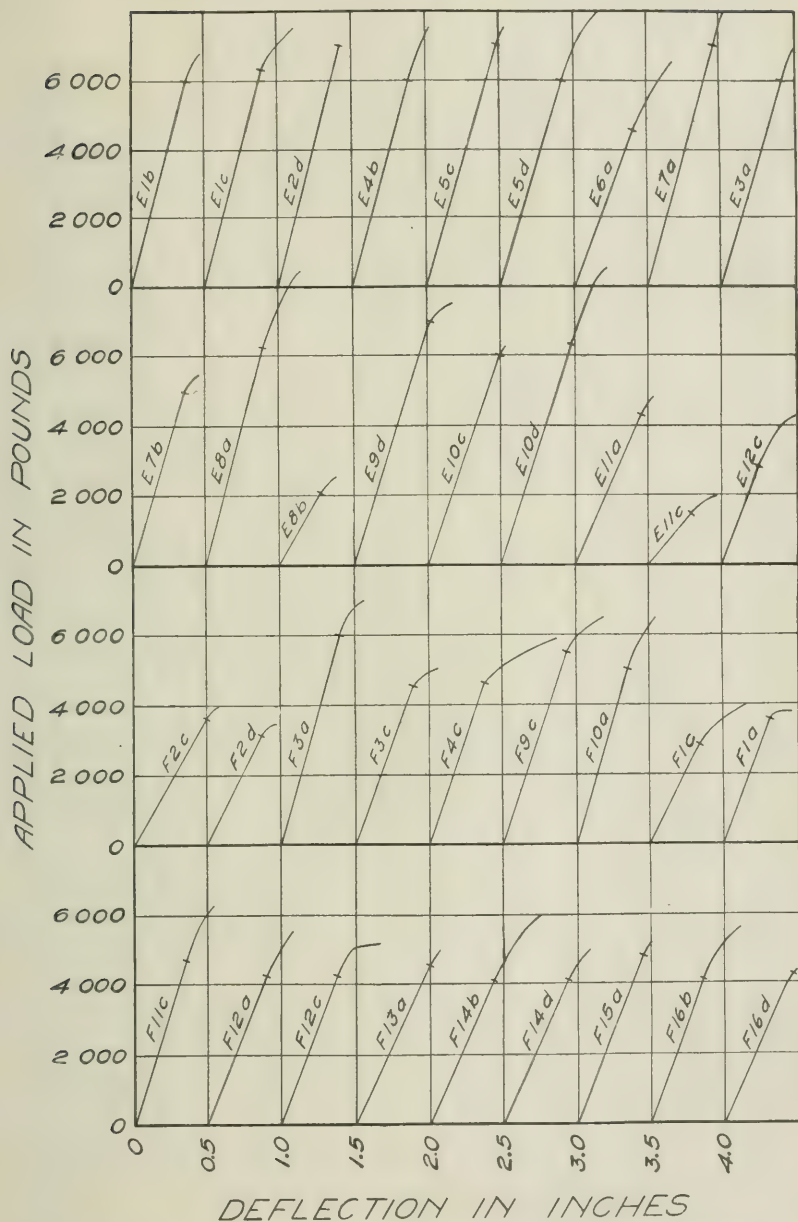


FIG. 23. LOAD-DEFLECTION DIAGRAMS FOR SMALL TEST BEAMS.

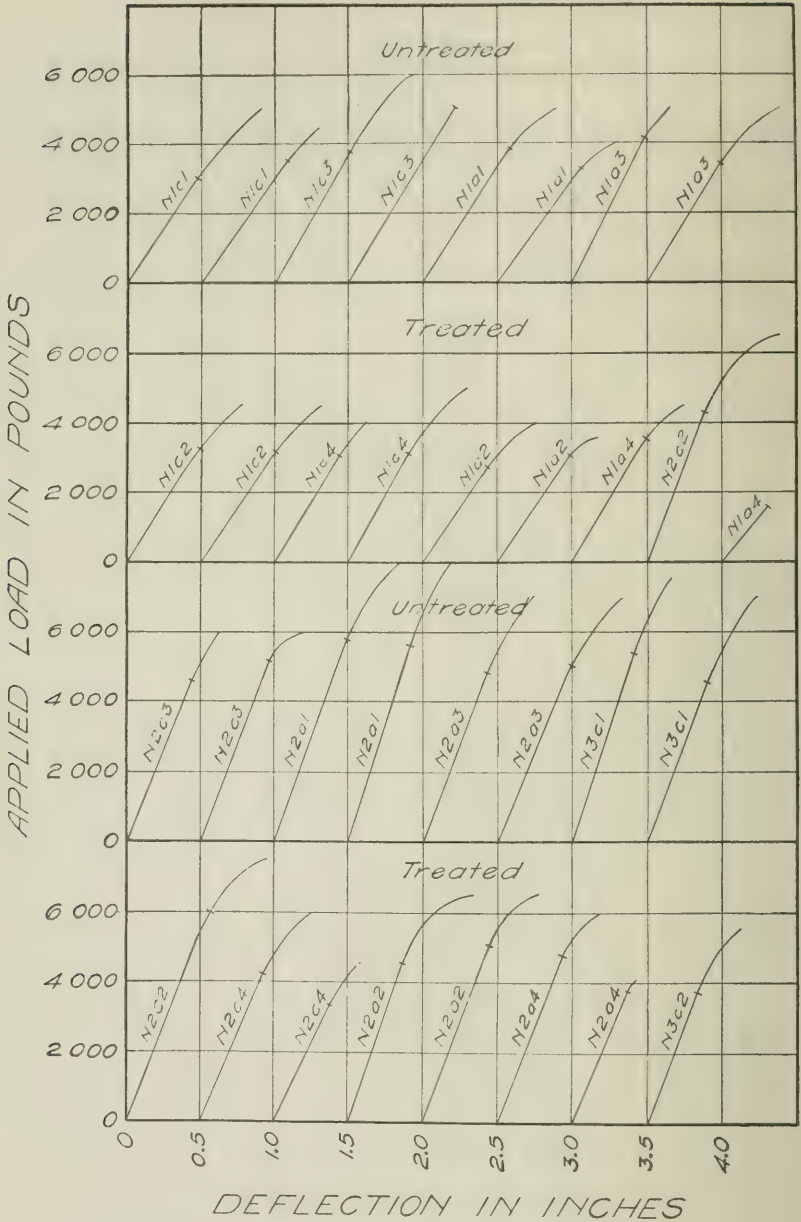


FIG. 24. LOAD-DEFLECTION DIAGRAMS FOR SERIES N.

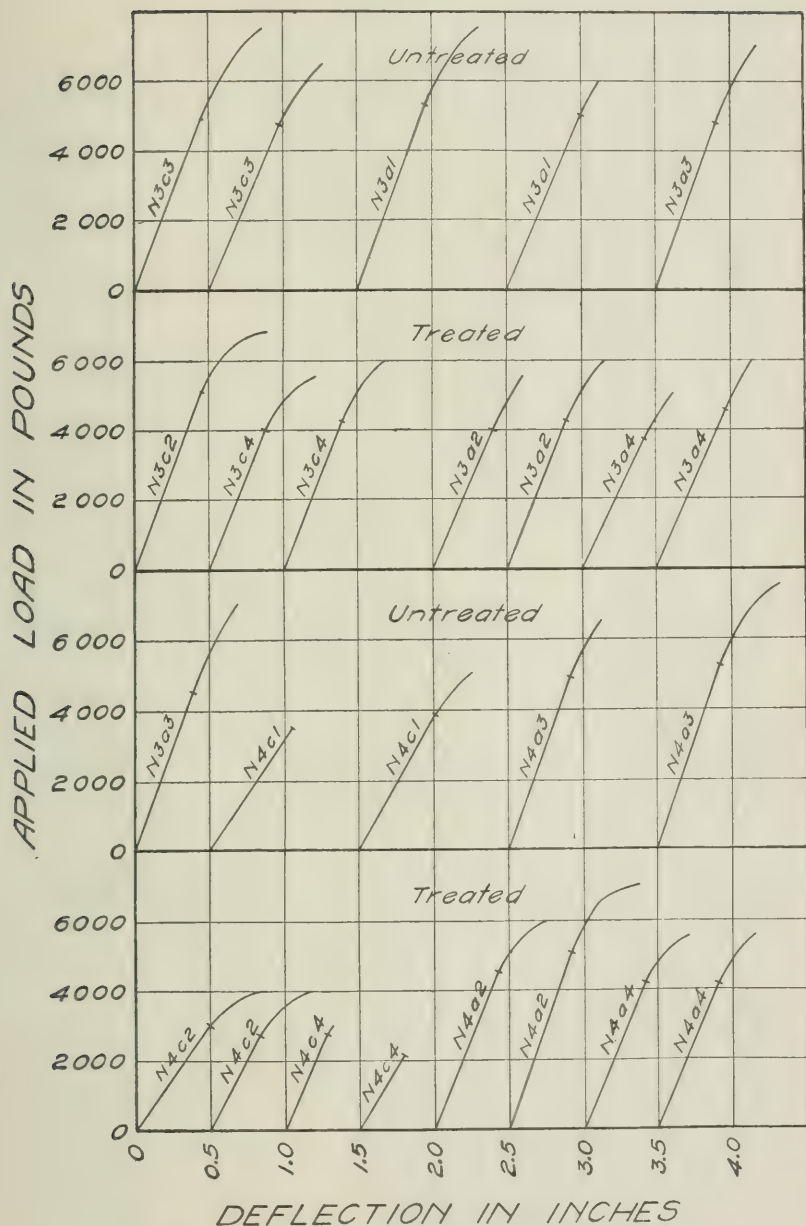


FIG. 25. LOAD-DEFLECTION DIAGRAMS FOR SERIES N.

PUBLICATIONS OF THE ENGINEERING EXPERIMENT STATION

- *Bulletin No. 1.* Tests of Reinforced Concrete Beams, by Arthur N. Talbot. 1904.
- *Circular No. 1.* High-Speed Tool Steels, by L. P. Breckenridge. 1905.
- *Bulletin No. 2.* Tests of High-Speed Tool Steels on Cast Iron, by L. P. Breckenridge and Henry B. Dirks. 1905.
- *Circular No. 2.* Drainage of Earth Roads, by Ira O. Baker. 1906.
- Circular No. 3.* Fuel Tests with Illinois Coal. (Compiled from tests made by the Technologic Branch of the U. S. G. S., at the St. Louis, Mo., Fuel Testing Plant, 1904-1907, by L. P. Breckenridge and Paul Diserens. 1909.
- *Bulletin No. 3.* The Engineering Experiment Station of the University of Illinois, by L. P. Breckenridge. 1906.
- *Bulletin No. 4.* Tests of Reinforced Concrete Beams, Series of 1905, by Arthur N. Talbot. 1906.
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- *Bulletin No. 19.* Comparative Tests of Carbon, Metallized Carbon and Tantalum Filament Lamps, by T. H. Amrine. 1908.
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- Bulletin No. 26.* High Steam-Pressures in Locomotive Service. A Review of a Report to the Carnegie Institution of Washington. By W. F. M. Goss. 1908.
- Bulletin No. 27.* Tests of Brick Columns and Terra Cotta Block Columns, by Arthur N. Talbot and Duff A. Abrams. 1909.
- Bulletin No. 28.* A Test of Three Large Reinforced Concrete Beams, by Arthur N. Talbot. 1909.
- Bulletin No. 29.* Tests of Reinforced Concrete Beams: Resistance to Web Stresses, Series of 1907 and 1908, by Arthur N. Talbot. 1909.
- Bulletin No. 30.* On the Rate of Formation of Carbon Monoxide in Gas Producers, by J. K. Clement, L. H. Adams, and C. N. Haskins. 1909.

PUBLICATIONS OF THE ENGINEERING EXPERIMENT STATION—*Continued*

- Bulletin No. 31.* Fuel Tests with House-heating Boilers, by J. M. Snodgrass. 1909.
- Bulletin No. 32.* The Occluded Gases in Coal, by S. W. Parr and Perry Barker. 1909.
- Bulletin No. 33.* Tests of Tungsten Lamps, by T. H. Amrine and A. Guell. 1909.
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- Bulletin No. 40.* A Study in Heat Transmission, by J. K. Clement and C. M. Garland. 1910.
- Bulletin No. 41.* Tests of Timber Beams, by Arthur N. Talbot. 1910.
- Bulletin No. 42.* The Effect of Keyways on the Strength of Shafts, by Herbert F. Moore. 1910.

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THE EFFECT OF KEYWAYS ON THE
STRENGTH OF SHAFTS

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APPLIED MECHANICS, ENGINEERING EXPERIMENT STATION

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THE EFFECT OF KEYWAYS ON THE STRENGTH OF SHAFTS.

I. INTRODUCTION.

1. *Preliminary.*—In the transmission of power by means of shafting and pulleys or gears, the common method of fastening the pulley or gear to the shaft, so that the two will rotate together, is by means of a key inserted in a keyway cut in the shaft, and extending into a corresponding keyway cut in the hub of the pulley or gear. The strength and the proper proportioning of keys have been subjects of considerable study and of some experimentation, but the effect of the keyway on the torsional strength of the shaft has apparently been studied but little. Evidently, the keyway must weaken the shaft in which it is cut. It would seem that the sharp corners of the keyway and its location at one side of the shaft might weaken the shaft more than the relatively small size of the keyway would lead us to expect. In view of the very extensive use of shafts with keyways and the small amount of information available on the subject, the effect of keyways on the torsional strength of shafts has seemed to the writer a problem worthy of some experimental study. This bulletin is an account of a brief investigation carried on in the Laboratory of Applied Mechanics by the Engineering Experiment Station of the University of Illinois.

The mathematical analysis of the strength of a shaft with a keyway cut in it is a problem of great complexity. The common theory of stresses in shafts applies only to shafts of circular cross-section. Mathematical researches by Saint Venant and others have developed the theory of square, rectangular, triangular, and elliptical shafts, but, so far as the writer knows, there has been no successful attempt to develop the mathematical theory of the stress in a shaft with a keyway cut in it. However, as the range of sizes of shafts and keys in common use is not very great, it was thought that an experimental study of the effect of keyways on the strength of shafts might lead to formulas which may be safely used in nearly all the cases met by the designer of shafts and keys.

It was found possible to investigate by direct experiment the effect of keyways on the strength of shafts of various sizes, and to study the effect of keyways on the strength of shafts subjected to combined bending and twisting.

For this use in calculation and design, it was thought best to coin a term to permit comparison between a shaft with keyway and an uncut shaft. Adopting a nomenclature similar to that used by many writers on the strength of riveted joints, the ratio of the strength of a shaft with a keyway to the strength of a similar shaft without a keyway is hereafter spoken of as the *efficiency of the shaft with keyway*.

If a shaft with a pulley keyed to it is given a permanent twist, the removal of the pulley is frequently a matter of great difficulty; while if a shaft carries a sleeve or gear with a key sliding in a keyway, any permanent twist practically ruins the shaft. For these reasons the elastic limit of a shaft under torsion is taken as the measure of its strength.

2. *Acknowledgment*.—A considerable part of the experimental work herein described was performed by the following senior students of the College of Engineering of the University of Illinois in the preparation of their graduating theses in Mechanical Engineering:

Mr. F. E. Leidendeker, Class of 1908.

Mr. O. Craig and Mr. J. C. Lund, Class of 1909.

The writer wishes to express his appreciation of the faithful and careful work of the above students. Acknowledgment is also made to the Whitney Manufacturing Company of Hartford, Connecticut, for cutters for keyways of the Woodruff system of keys.

The work was undertaken with the approval of Professor Arthur N. Talbot, head of the department of Theoretical and Applied Mechanics, to whom the writer is indebted for many helpful suggestions, both as to methods of experimentation and to interpretation and arrangement of results.

3. *Notation and Formulas*.—The following notation is used:

d = actual diameter of shaft in inches.

w = width of keyway $\div$ diameter of shaft.

h = depth of keyway $\div$ diameter of shaft.

T = torsional (twisting) moment on shaft in inch pounds.

M = bending moment on shaft in inch-pounds.

J = polar moment of inertia of cross-section of shaft
(for circular shaft, $J = \frac{d^4}{10.2}$).

f = greatest fiber stress in shaft due to torsion.

Θ = angle of twist of shaft in degrees.

l = length of shaft in inches.

E_s = modulus of elasticity of material of shaft in shear (torsion).

e = efficiency of shaft with keyway.

k = ratio of angle of twist of shaft with keyway to angle of twist of similar uncut shaft.

$H. P.$ = horse-power.

$r. p. m.$ = number of revolutions per minute.

The following formulas are used:

$$T = \frac{2fJ}{d}$$

$$\Theta = \frac{2fl}{E_s d} \times 57.3$$

$$T = 63\,020 \frac{H. P.}{r. p. m.}$$

The first two formulas are based on the following assumptions; (1) that a plane section of the shaft remains plane during torsion; and (2) that the fiber stress varies uniformly from zero at the axis of the shaft to a maximum at the outer fiber, i. e., the modulus of elasticity for shear remains constant. The first assumption is not true for shafts which are not circular in cross-section.

II. TEST PIECES, TESTS, AND METHOD OF TESTING.

4. *Test Pieces.*—The principal object of this investigation was to obtain values of the efficiency of shafts with keyways, and as nearly all shafting in common use is cold-rolled, the principal series of tests was made on specimens of cold-rolled steel shafting. The diameters of the test shafts of these series were $1\frac{1}{4}$, $1\frac{1}{16}$, $1\frac{1}{8}$, and $2\frac{1}{4}$ in. Shafts were tested under simple torsion and under torsion combined with bending. The bending moment applied to the shaft was in one case equal to the torsional moment, and in another equal to three-fifths the torsional moment. Table 1 shows the sizes of shafts and the sizes of the keyways cut in them.

TABLE 1.
DIMENSIONS OF SHAFTS AND KEYWAYS.
SERIES OF 1909.

Dia. Shaft inches d	Relative Dimensions of Keyway		Actual Dimensions of Keyway inches	
	w	h	width	depth
$1\frac{1}{4}$	0.25	0.125	$\frac{5}{16}$	0.156
	0.50	0.125	$\frac{9}{16}$	0.156
	0.25	0.1875	$\frac{5}{8}$	0.234
$1\frac{1}{2}$	0.25	0.125	$\frac{5}{8}$	0.195
	0.50	0.125	$\frac{7}{8}$	0.195
	0.25	0.1875	$\frac{1}{1}$	0.293
$1\frac{3}{4}$	0.25	0.125	$\frac{3}{4}$	0.242
	0.50	0.125	$\frac{7}{8}$	0.242
	0.25	0.1875	$\frac{1}{1}$	0.363
$2\frac{1}{4}$	0.25	0.125	$\frac{1}{1}$	0.281
	0.50	0.125	$1\frac{1}{8}$	0.281
	0.25	0.1875	$1\frac{1}{2}$	0.422

For transmitting power, it is common American practice to use a square key whose width and depth are each equal to about one-fourth the diameter of the shaft (Kent's Pocket-Book, pp. 975 - 976). This means a keyway in the shaft in which $w = 0.25$ and $h = 0.125$. The depth of keyway is measured as shown in Fig. 1.

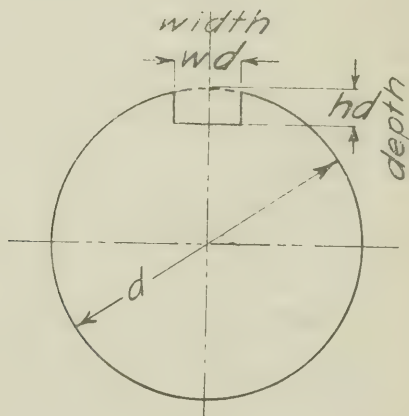


FIG. 1.

Shafts were also tested with keyways for the Woodruff system of keying. The outline of the Woodruff key and its keyway

are shown in Fig. 2. In choosing the sizes of Woodruff keyways to be cut in the test shafts, the shearing strengths of various standard sizes of keys were figured, and a standard size was

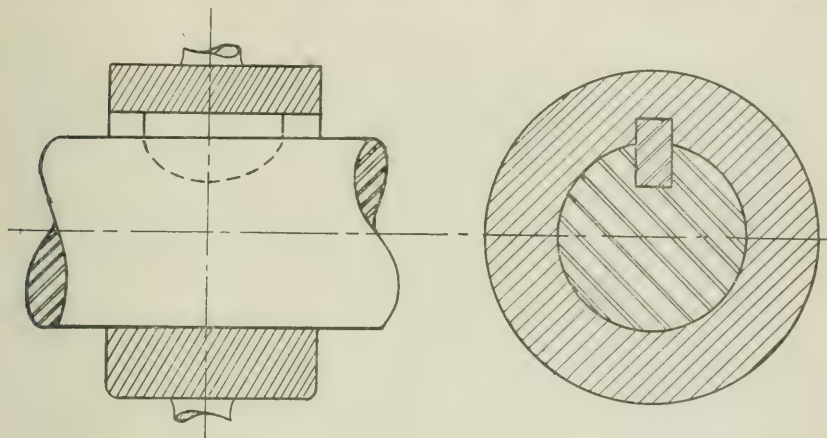


FIG. 2.

chosen such that the shearing strength of two keys equaled, as nearly as possible, the torsional strength of the solid test shaft in question. The sizes of the Woodruff keys chosen are shown in Tables 2 and 4.

In addition to the above tests for effect of single keyways on the strength of cold-rolled shafting, tests were made (principally in the 1908 series) which yielded data on the following subjects: ultimate strength of shafts with keyways; effect of two keyways at right angles; effect of length of keyway; effect of keyways on turned steel shafting.

All keyways, except in the tests for studying the effect of length of keyways, were cut to a length equal to about four times the diameter of the shaft, no keyway being longer than eight inches.

All material for the test shafts was bought in the open market. Both the cold-rolled and the turned shafting were of ordinary soft steel. All tests were planned in duplicate, and with a very few exceptions, all tests were made in duplicate.

5. *Description of Apparatus.*—All shafts tested under simple twisting were tested in the 230 000 in.-lb. Olsen torsion testing machine in the Laboratory of Applied Mechanics of the Univer-

sity of Illinois. To the test shaft were attached long arms in pairs, one arm of a pair carrying a pointer, and the other a scale. The angle of twist between these two arms was measured by the motion of the pointer over the scale. Fig. 3 shows a test shaft

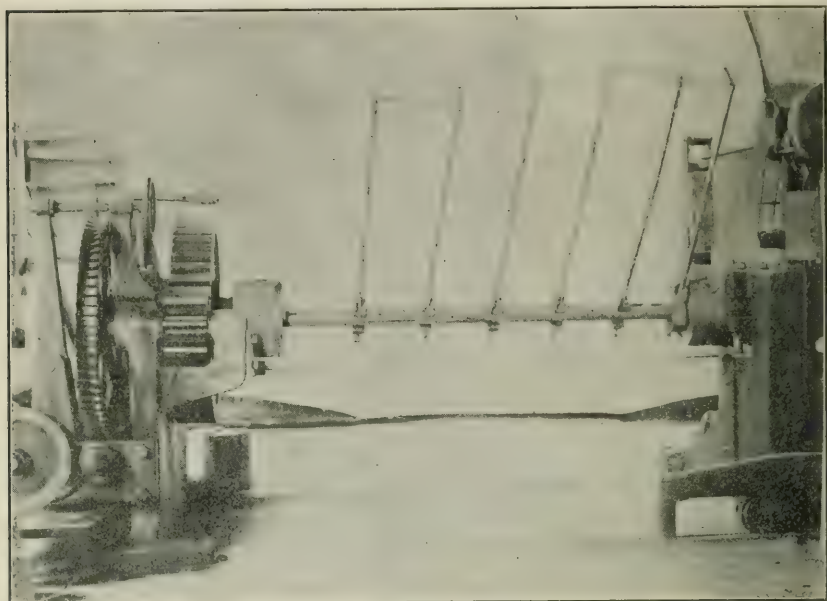


FIG. 3.

of the 1909 series in position with the pointers and scales attached. In this shaft were cut four keyways, each keyway being 90° round the shaft from the adjacent keyways. The angle of twist of the shaft was measured over five portions of its length, four portions of length being occupied by the keyways and one being without keyway. The latter portion was generally at the middle of the shaft.

The apparatus used for studying the effect of combined twisting and bending on shafts with keyways is shown in Fig. 4. To the ends of the test shaft *S* were keyed arms *AA* extending at right angles to the shaft. Equal forces *FF* were applied in a vertical direction at points on these arms at a distance *p* from the axis of the shaft. The test shaft was supported on bearings *GG* by means of steel balls *B*, bearing on hardened steel bushings.

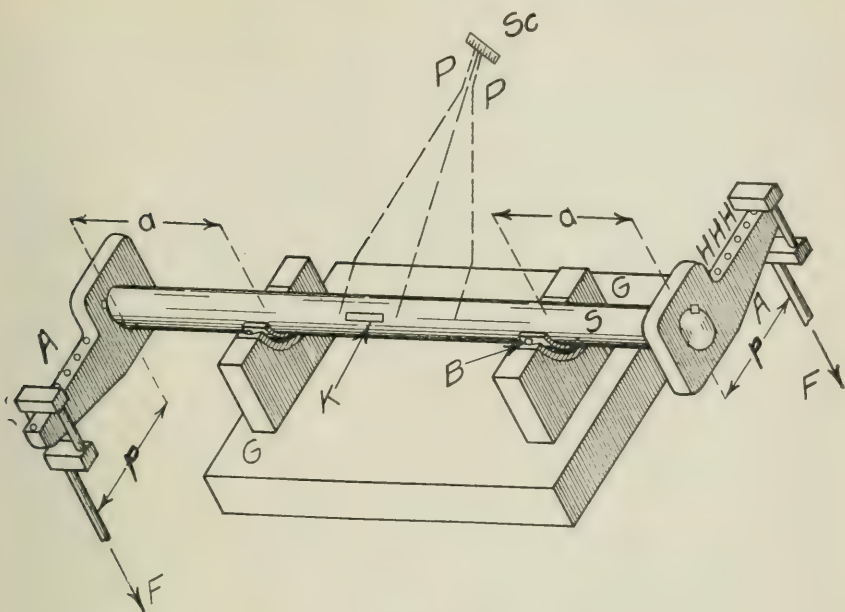


FIG. 4.

The distance a from the arm A to the center of the nearer bearing was the same at the two ends. The test shaft then was subjected to a bending moment Fa over that portion between bearings, and to a twisting moment Fp over its entire length (the very small friction of the ball bearings being neglected). The ratio of the twisting moment to the bending moment equals $\frac{p}{a}$.

The forces FF were applied by the moving crosshead of a testing machine. The entire apparatus shown in Fig. 4 rested on the upper weighing head of the testing machine. The load registered on the weighing table of the machine was equal to $2F$. The force F was transmitted to each of the arms AA through a small spherical pointed knob resting in one of the holes $HHHH$, the twisting arm being varied by using different holes. The bearings GG could be moved axially along the shaft, thus allowing the bending moment to be varied. In the tests under combined twisting and bending, the keyway cut in the test shaft was located at one side of the center of the shaft, and the angle of twist was measured over the portion of the shaft containing the keyway,

and also over the solid portion. The apparatus for measuring angle of twist was the same as in the tests under simple torsion, and is shown in the diagram in Fig. 4, in which K represents the keyway, PP the pointers, and Sc the scale.

6. *Procedure of Tests.*—In the 1908 tests, which were all on shafts under twisting only, the method of conducting the test was to apply torsion continuously until the yield point was passed, frequent readings of twisting moment and of corresponding angle of twist being taken. After the yield point was passed, the twist-measuring apparatus was removed, and the torsion applied until the shaft broke, the maximum twisting moment carried being noted.

In the 1909 tests, both under simple torsion and under combined twisting and bending, the method of procedure was as follows: A small initial load was applied to the shaft, and an initial reading taken on the twist-measuring apparatus; more load was then applied and the angle of twist read; the load was then released to its initial value, and the angle of twist again read, any permanent set being thus detected; a load slightly greater than the previously applied load was then put on the shaft, and this load in turn released to the initial value. This process was repeated with applications of increasing loads until the yield point of the shaft was passed.

III. DATA AND RESULTS.

7. *Ultimate Strength of Shafts with and without Keyways.*—Table 2 (tests of 1908) shows the results of tests to breaking of shafts with and without keyways. It seems that a shaft with a single keyway of common dimensions has about the same ultimate strength as a shaft without keyway. In the torsional tests to destruction, after the elastic limit of the shaft had been passed, the keyways gradually closed up and at rupture they were entirely closed. The larger keyways and the two keyways 90° apart lowered the ultimate strength somewhat. The variation in strength due to difference in material of the shafting seems to cause more variation in ultimate strength than is caused by different keyways. As previously pointed out, the elastic limit of a shaft is more significant than its ultimate strength.

TABLE 2.

ULTIMATE STRENGTH OF SHAFTS WITH KEYWAYS AND WITHOUT KEYWAYS.

Values are the average results of two tests.

Diameter of Shaft inches	Keyway		Maximum Twisting Moment in.-lb.	Maximum Computed Fiber Stress (solid shaft) lb. per sq. in.	H. P. 100 r.p.m.	Remarks
	Width inches	Depth inches				
1¼ in. cold- rolled	0	0	27 400	70 550	43.4	Shaft without keyway
	¼	¼	27 600	71 000	43.8	
	¾	¼	30 300	78 000	48.0	
	¾	¾	24 400	63 000	38.7	
	¾	½	27 600	71 000	43.8	
	¾	⅝	27 200	70 000	43.1	
1¼ in. turned	No. 10	No. 10	25 500	65 800	40.4	Keyway for No. 10 Woodruff
	No. 15	No. 15	26 200	67 600	41.6	Keyway for No. 15 Woodruff
	¾	¼	25 300	65 200	40.1	2 keyways 90° apart
	0	0	25 300	65 200	40.1	Shaft without keyway
	¼	¼	25 800	66 400	40.9	
	¾	¾	25 500	65 700	40.4	
1% in. cold- rolled	No. 10	No. 10	23 700	61 000	37.6	Keyway for No. 10 Woodruff
	No. 15	No. 15	24 100	62 100	38.2	Keyway for No. 15 Woodruff
	0	0	54 700	65 000	86.8	Shaft without keyway
2 in. cold- rolled	½	½	56 400	67 000	89.6	
	0	0	103 700	66 000	164.5	Shaft without keyway
	⅞	⅞	102 100	65 000	162.0	
	1½	1½	101 500	64 600	161.1	
	1½	1½	94 200	60 000	149.1	
	1½	¾	104 500	66 500	165.7	
2 in. turned	No. 16	No. 16	105 300	67 000	167.0	Keyway for No. 16 Woodruff
	No. 21	No. 21	100 500	64 000	158.7	Keyway for No. 21 Woodruff
	0	0	100 500	64 000	158.7	Shaft without keyway
	⅞	⅞	94 200	60 000	149.1	
	1½	¾	94 200	60 000	149.1	
	No. 16	No. 16	89 800	57 200	142.5	Keyway for No. 16 Woodruff
	No. 21	No. 21	85 000	54 100	134.8	Keyway for No. 21 Woodruff

8. *Effect of Length of Keyway.*—Several special tests were made on the effect of keyways on the strength of shafts. In general, these tests, while too few in number to justify final conclusions, gave suggestive or tentative results.

The keyways in nearly all the shafts tested were cut to a total length of about four times the diameter of the shaft, no keyway being longer than 8 inches; but in several special shafts, keyways were cut 18 inches long. No difference between *strength* of shafts with long keyways and of similar shafts with the usual shorter keyways was observed.

9. *Effect of Two Keyways 90° Apart.*—One test was made of a shaft having cut in it two keyways 90° apart, the two keyways

being located in the same cross-section of the shaft. While the result of this single test is by no means conclusive, it is of interest to note that the reduction in strength at elastic limit of the shaft by these two keyways was nearly three times as great as the reduction in strength at elastic limit of a similar shaft by one such keyway.

10. *Effect of Keyways on Turned Shafting.*—The tests made were mainly on cold-rolled shafting, but in the 1908 series a few tests were made on test specimens of turned shafting. Owing to the imperfect method used in the 1908 tests for locating the elastic limit, these results must be regarded as tentative. In these tests the effect of keyways on the strength of turned shafting at the elastic limit seemed to be about the same as the effect of keyways on the strength of cold-rolled shafting.

11. *Strengthening Effect of Key in Place.*—During the tests, the question arose as to the difference in strength of a shaft with empty keyway and a shaft on which a pulley was keyed in place, the key nearly filling the keyway. It was judged best, however, to test shafts with empty keyways, as there is usually a part of the keyway at either end not filled by the key, and a perfect fit of the key in the keyway is by no means certain, especially after long service and, therefore, for purposes of design the empty keyway determines the strength of the shaft.

TABLE 3.

RATIO OF ANGLE OF TWIST OF SHAFT WITH KEYWAY
TO ANGLE OF TWIST OF SIMILAR SHAFT
WITHOUT KEYWAY.

Diameter of Shaft inches	Dimensions of Keyway			
	$w = 0.25$ $h = 0.125$	$w = 0.25$ $h = 0.1875$	$w = 0.50$ $h = 0.125$	Woodruff System*
1 $\frac{1}{4}$	1.24	1.25	1.27	1.11
1 $\frac{3}{8}$	1.14	1.24	1.19	1.11
	1.18	1.21	1.36	1.18
1 $\frac{1}{2}$	1.16	1.21	1.41	1.11
	1.29	1.48	1.54	1.12
2 $\frac{1}{4}$	1.10	1.25	1.18	1.05
	1.10	1.28	1.37	1.10
Average	1.17	1.27	1.33	1.11

*See Table 4 for sizes of Woodruff Keyways.

12. *Effect of Keyway on Stiffness of Shaft.*—The amount of twist in a shaft transmitting power is frequently of importance. Table 3 gives the ratio of angle of twist of shafts with keyways to angle of twist of shafts without keyways as computed from the data of the torsional tests for stresses within the elastic limit. The results are fairly well represented by the equation

$$k = 1.0 + 0.4 w + 0.7 h,$$

in which k = ratio of angle of twist of shaft with keyway to angle of twist of similar shaft without keyway, w = width of keyway $\div$ diameter of shaft, and h = depth of keyway $\div$ diameter of shaft.

Keyways for two Woodruff keys of shearing strength sufficient to develop the full twisting strength of shaft seemed to reduce the stiffness of the shaft somewhat less than did a keyway for a square key whose side measures one-fourth the diameter of the shaft.

In considering the torsional stiffness of a shaft, it must be remembered that the keyways reduce the stiffness only over that portion of length which they actually occupy.

13. *Efficiency of Shafts with Keyways.*—The efficiency of a shaft with keyway has already been defined as the ratio of strength at elastic limit of a shaft with keyway to the strength at elastic limit of a similar shaft without keyway.

The determination of the elastic limit of a shaft under torsion is somewhat difficult; when the outer fibers are stressed to the elastic limit, the stress is taken more largely by the inner fibers, and the change of angle of twist is not so sudden as is the change of stretch at the elastic limit in a piece under tension, where the fibers are stressed nearly uniformly, and all begin to yield at nearly the same time. In the 1908 tests, each test shaft carried only a single keyway, and comparison between the strength of shafts with keyways and the strength of similar shafts without keyways was made by testing different specimens. This allowed a comparison of the ultimate strengths, which are very clearly defined; but in comparing elastic limits, the variation between the material of different specimens was sufficiently great to throw some doubt on the accuracy of the efficiency of shafts with keyways, as determined by this method. In the 1909 tests, the elastic limit of a section of shaft with keyway was compared with

that of an adjacent section without keyway in the same shaft. Thus the error due to difference in material was greatly reduced, but by this method the ultimate strength of only the weakest section of the shaft could be obtained. So while all the results on ultimate strength have been obtained from the 1908 tests, the efficiencies of the shafts with keyways have been obtained entirely from the 1909 tests.

In computing results, J. B. Johnson's method of locating the elastic limit was found most satisfactory*. Fig. 5 to 12 give the deformation and set curves for the 1909 series of tests. The solid lines show the deformation (angle of twist) under load, while the broken lines show the set. The elastic limit as determined by Johnson's method is shown on each curve by a short line drawn across the deformation curve, and it will be noted that the stress at which noticeable permanent set begins is in all cases nearly the same as the stress at the elastic limit as determined by Johnson's method.

Table 4 shows the efficiency of the various test shafts of the 1909 series of tests, using the term efficiency as previously defined. From this table it would appear that for a set of shafts of different sizes having the dimensions of the keyway kept proportional to the diameter of shaft, the efficiency does not depend, in any noticeable degree, on the size of shaft. The efficiency does not seem to be affected by the addition of a bending moment as great as the twisting moment. The efficiency of a shaft with two keyways cut in the same plane for two Woodruff keys, of such size that the strength of solid shaft was equal to the shearing strength of the two Woodruff keys, is about the same as the efficiency of a shaft with a keyway whose width equals one-fourth the diameter of the shaft and whose depth equals one-eighth the diameter of the shaft.

The results of the foregoing tests are fairly well represented by the equation

$$e = 1.0 - 0.2 w - 1.1 h$$

in which

e = efficiency of shaft with keyway,

w = width of keyway $\div$ diameter of shaft,

h = depth of keyway $\div$ diameter of shaft.

*J. B. Johnson's method of locating the elastic limit consists in finding the point on the stress-deformation curve at which the deformation is increasing fifty per cent more rapidly than its initial rate of increase. See Johnson's "Materials of Construction", pp. 18-20.

TABLE 4.

EFFICIENCY OF SHAFTS WITH KEYWAYS.

$$\frac{1}{2} \text{ Efficiency} = \frac{\text{elastic strength of shaft with keyway}}{\text{elastic strength of shaft without keyway}}$$

Dimensions of Keyway	$w = 0.50$ $h = 0.125$	$w = 0.25$ $h = 0.1875$	$w = 0.25$ $h = 0.125$	Woodruff System*
Under simple torsion:				
Cold-rolled shaft, dia. $1\frac{1}{4}$ in.	0.762	0.760	0.820	0.940
Cold-rolled shaft, dia. $1\frac{3}{8}$ in.	0.803	0.846	0.900	0.860
	0.758	0.817	0.889	0.815
Cold-rolled shaft, dia. $1\frac{1}{2}$ in.	0.748	0.710	0.860	0.826
	0.764	0.750	0.824	0.835
Cold-rolled shaft, dia. $2\frac{1}{4}$ in.	0.848	0.775	0.839	0.943
	0.705	0.689	0.825	0.861
Under combined torsion and bending:				
1. Twisting moment = Bending moment	0.630	0.636	0.791	0.716
Cold-rolled shaft, dia. $1\frac{1}{4}$ in.	0.680	0.698	0.803	0.750
Cold-rolled shaft, dia. $1\frac{1}{2}$ in.	0.584	0.697	0.854	0.858
	0.671	0.775	.....	0.840
2. Twisting moment = $\frac{2}{3}$ Bending moment	0.895	0.670	0.940	0.930
Cold-rolled shaft, dia. $1\frac{1}{4}$ in.	0.870	0.735	0.888	0.880
Cold-rolled shaft, dia. $1\frac{1}{2}$ in.	0.740	.....	0.832	0.856
	0.815	.....	0.840	0.810
General Average	0.752	0.735	0.850	0.845

*In $1\frac{1}{4}$ -in. shafts keyways were cut for No. 15 Woodruff keys

$1\frac{3}{8}$ -in. shafts keyways were cut for No. 25 Woodruff keys

$1\frac{1}{2}$ -in. shafts keyways were cut for No. S Woodruff keys

$2\frac{1}{4}$ -in. shafts keyways were cut for No. U Woodruff keys

This equation gives efficiencies slightly lower than those observed for keyways of small width or depth, and efficiencies about the same as those observed for keyways in which $w = 0.50$ and $h = 0.125$; or $w = 0.25$ and $h = 0.1875$. As this equation is entirely dependent on the results of experiments, it should not be used for points much outside the limits of the experiments. The limits of the above series of tests were keyways having $w = 0.50$ and $h = 0.1875$.

Fig. 13 affords a convenient graphical method of applying the above formula, and is used as follows: To determine the efficiency of a shaft with a given (or proposed) keyway, locate on the diagram a point whose vertical distance from 0 equals the value of h , and whose horizontal distance from 0 equals the value of w . This point will, in general, fall between two lines representing values of efficiency, and the efficiency of the shaft in question may then be estimated with sufficient accuracy. The space within the triangle OAB represents the range covered by the

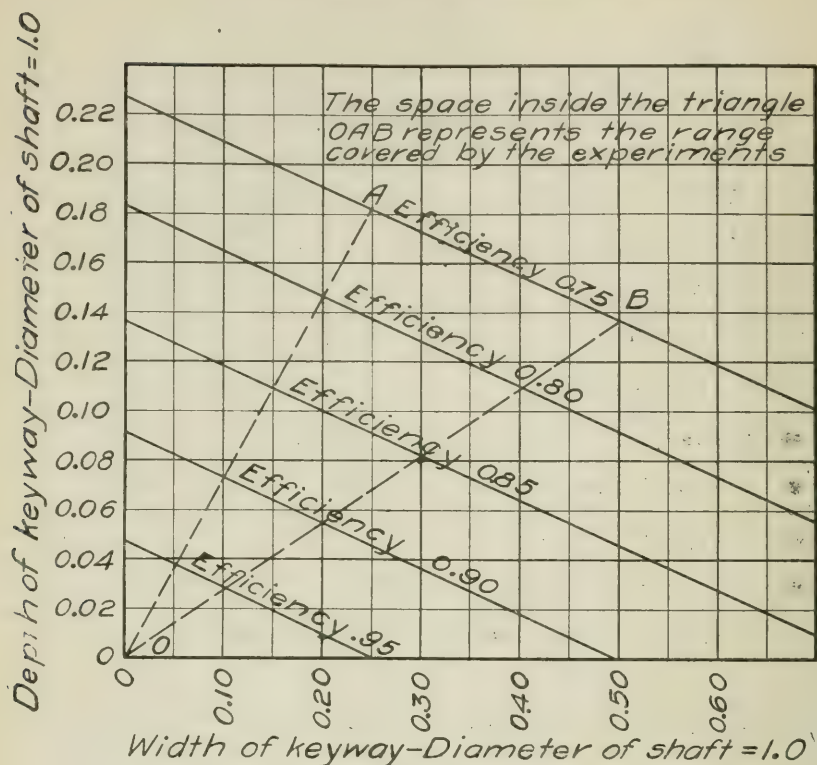


FIG. 13.

tests actually performed, and covers the proportions of keyways commonly used in practice.

14. *Torsional Strength of Shafts with Keyways.*—The object of these tests was to determine ratios of strength and stiffness between shafts with keyways and shafts without keyways. The number of tests was not sufficient to give very much information as to the properties of cold-rolled steel shafting. However, as a matter of general interest, the values found in these tests for the modulus of elasticity in shear (torsion), and of the fiber stress at the elastic limit of the cold-rolled test shafts at sections without keyway, have been tabulated in Tables 5 and 6.

Taking the fiber stress at the elastic limit of cold-rolled steel shafting at 37 500 lb. per sq. in. (a value slightly less than the average found in the tests), and the efficiency of shafts with keyways from the equation $e = 1.0 - 0.2 w - 1.1 h$, values for the

TABLE 5.
MODULUS OF ELASTICITY IN
SHEAR (TORSION) OF COLD-
ROLLED STEEL SHAFTING.

Test No.	Diameter of Shaft inches	Modulus of Elasticity
46	1 $\frac{1}{4}$	12 900 000
47	1 $\frac{3}{8}$	12 000 000
48	1 $\frac{3}{8}$	12 490 000
49	1 $\frac{3}{8}$	10 800 000
50	1 $\frac{3}{8}$	12 660 000
51	2 $\frac{1}{4}$	11 340 000
52	2 $\frac{1}{4}$	11 710 000
	Average	11 985 000

TABLE 6.
ELASTIC LIMIT IN TORSION
OF COLD-ROLLED STEEL
SHAFTING.

Test No.	Diameter of Shaft inches	Fiber Stress lb. per sq. in.
46	1 $\frac{1}{4}$	43 300
47	1 $\frac{3}{8}$	36 800
48	1 $\frac{3}{8}$	38 500
49	1 $\frac{3}{8}$	36 800
50	1 $\frac{3}{8}$	40 500
51	2 $\frac{1}{4}$	36 200
52	2 $\frac{1}{4}$	40 500
	Average	38 940

twisting moments and the horse-power at 100 r.p.m., transmitted by cold-rolled shafts stress to the elastic limit, have been computed for various sizes and tabulated in Table 7. These values are for shafts with keyways for square keys whose side measures about one-fourth the diameter of the shaft. In the use of this table, a suitable factor of safety should be allowed.

TABLE 7.

STRENGTH OF SHAFTS WITH KEYWAY.

The table gives the calculated twisting moment and horse-power at 100 r. p. m., transmitted in torsion by cold-rolled shafting with keyway when stressed to the elastic limit. Fiber stress is assumed at 37 500 lb. per sq. in. The keyway is cut for a square key whose side measures approximately one-fourth the diameter of the shaft. No allowance is made for bending action. In applying this table, a suitable factor of safety should be used.

Diameter of Shaft inches	Side of Key inches	Twisting Moment in.-lb.	Horse-power at 100 r. p. m.
1	$\frac{1}{4}$	5 980	9.5
$1\frac{1}{16}$	$\frac{3}{8}$	7 080	11.2
$1\frac{1}{8}$	$\frac{3}{8}$	8 510	13.5
$1\frac{1}{4}$	$\frac{3}{8}$	9 980	15.7
$1\frac{1}{2}$	$\frac{3}{8}$	11 680	18.5
$1\frac{5}{8}$	$\frac{3}{8}$	13 390	21.3
$1\frac{3}{4}$	$\frac{3}{8}$	15 550	24.7
$1\frac{7}{8}$	$\frac{3}{8}$	17 590	27.9
$1\frac{9}{8}$	$\frac{3}{8}$	20 190	32.0
$1\frac{11}{8}$	$\frac{3}{8}$	22 600	35.9
$1\frac{5}{4}$	$\frac{3}{8}$	25 660	40.7
$1\frac{13}{8}$	$\frac{3}{8}$	28 500	45.2
$1\frac{3}{2}$	$\frac{3}{8}$	32 060	50.9
$1\frac{7}{4}$	$\frac{3}{8}$	35 350	56.1
$1\frac{9}{4}$	$\frac{3}{8}$	39 420	62.6
$1\frac{11}{4}$	$\frac{3}{8}$	43 180	68.5
2	$\frac{3}{8}$	47 860	75.9
$2\frac{1}{16}$	$\frac{3}{8}$	52 140	82.7
$2\frac{1}{8}$	$\frac{3}{8}$	57 900	91.1
$2\frac{1}{4}$	$\frac{3}{8}$	62 210	98.7
$2\frac{3}{8}$	$\frac{3}{8}$	68 180	108.2
$2\frac{1}{2}$	$\frac{3}{8}$	73 490	116.6
$2\frac{5}{8}$	$\frac{3}{8}$	80 120	127.1
$2\frac{3}{4}$	$\frac{3}{8}$	86 080	136.6
$2\frac{7}{8}$	$\frac{3}{8}$	93 470	148.3

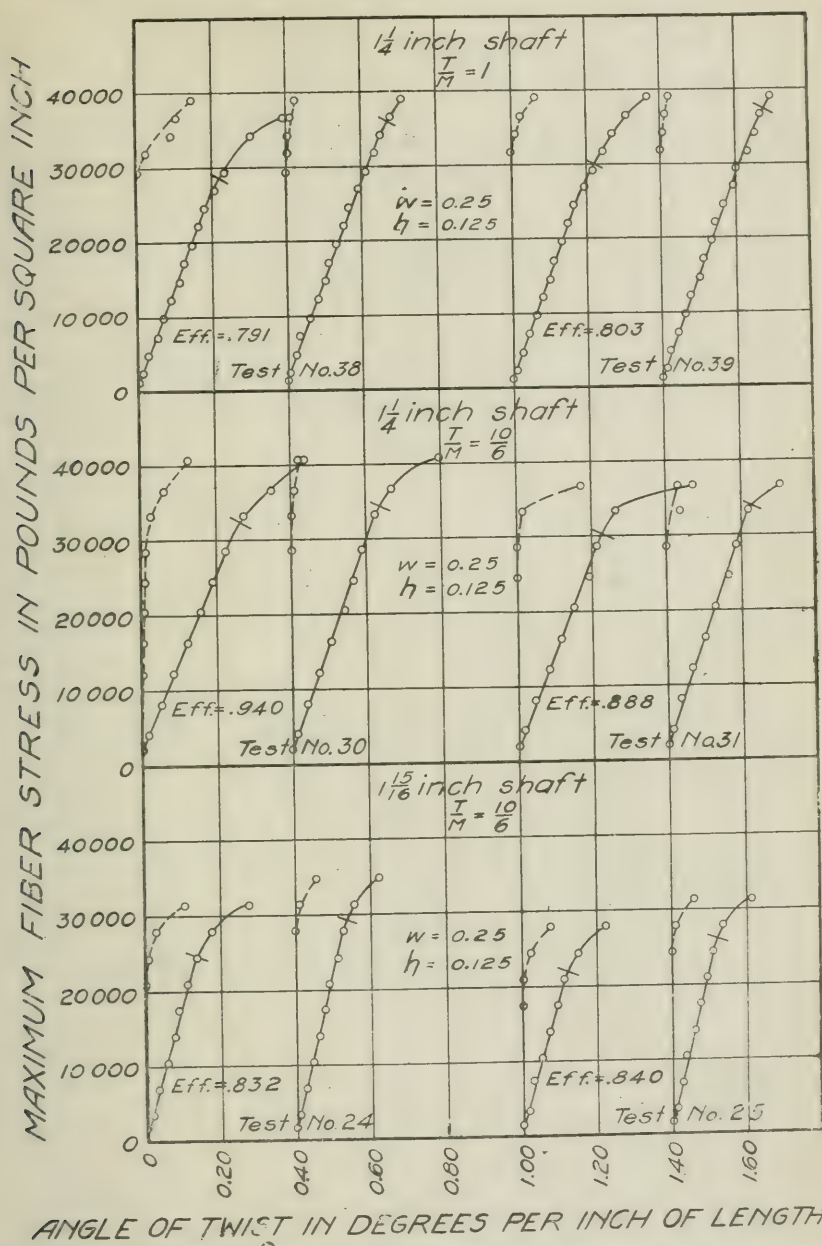


FIG. 5. DIAGRAMS OF TESTS UNDER COMBINED BENDING AND TWISTING.

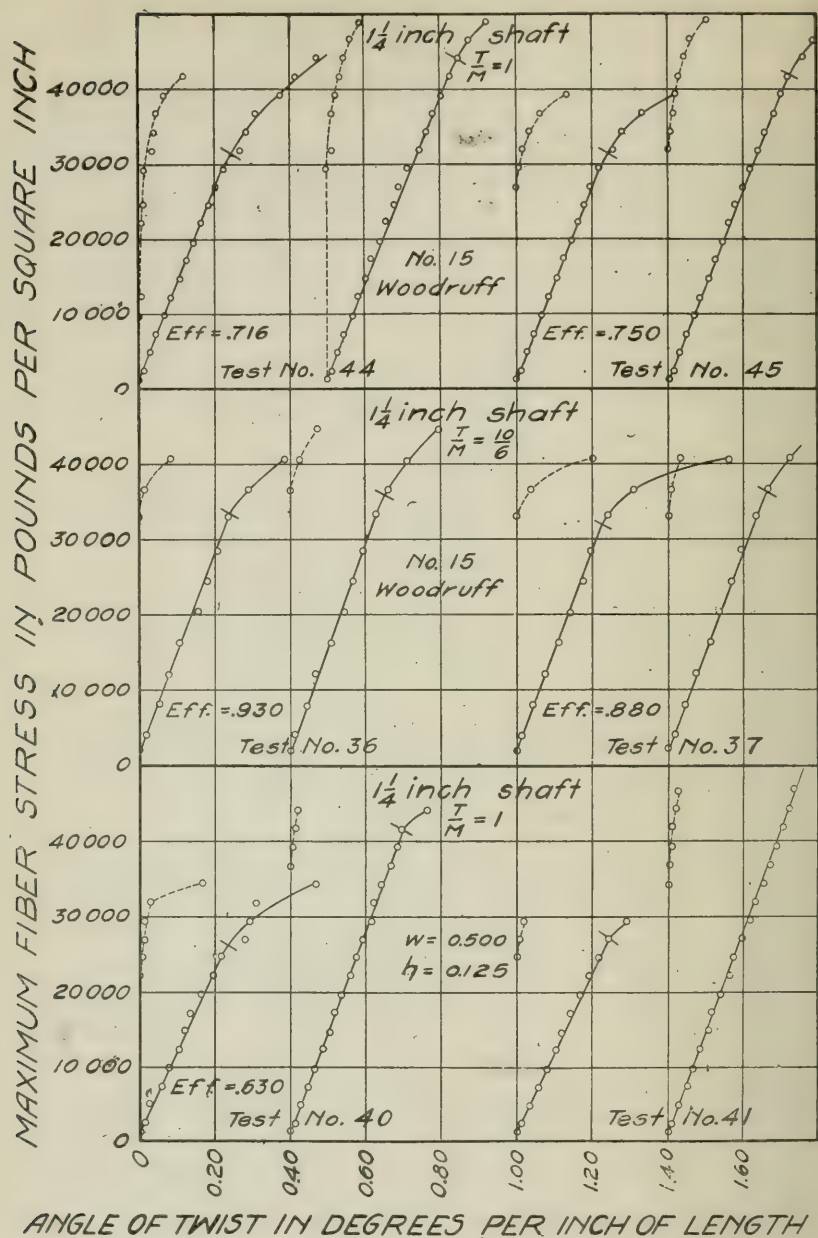


FIG. 6. DIAGRAMS OF TESTS UNDER COMBINED BENDING AND TWISTING.

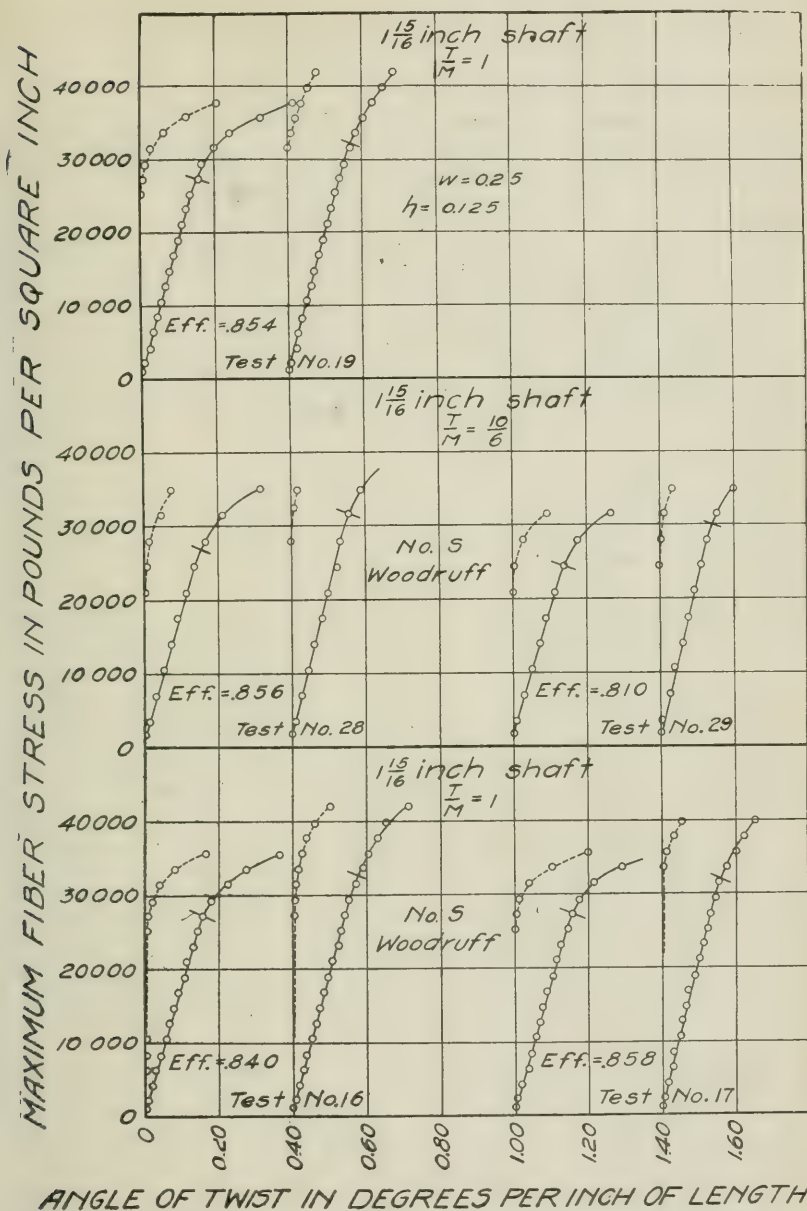


FIG. 7. DIAGRAMS OF TESTS UNDER COMBINED BENDING AND TWISTING.

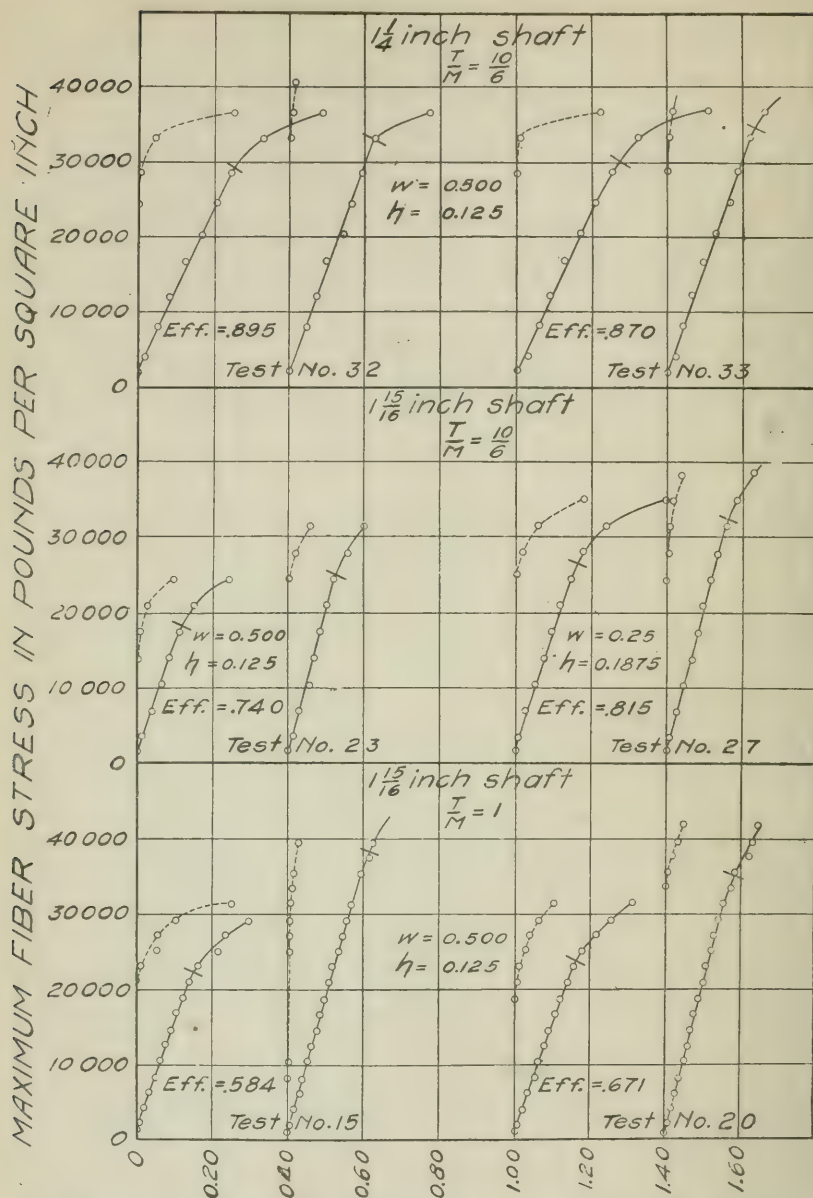


FIG. 8] DIAGRAMS OF TESTS UNDER COMBINED BENDING AND TWISTING

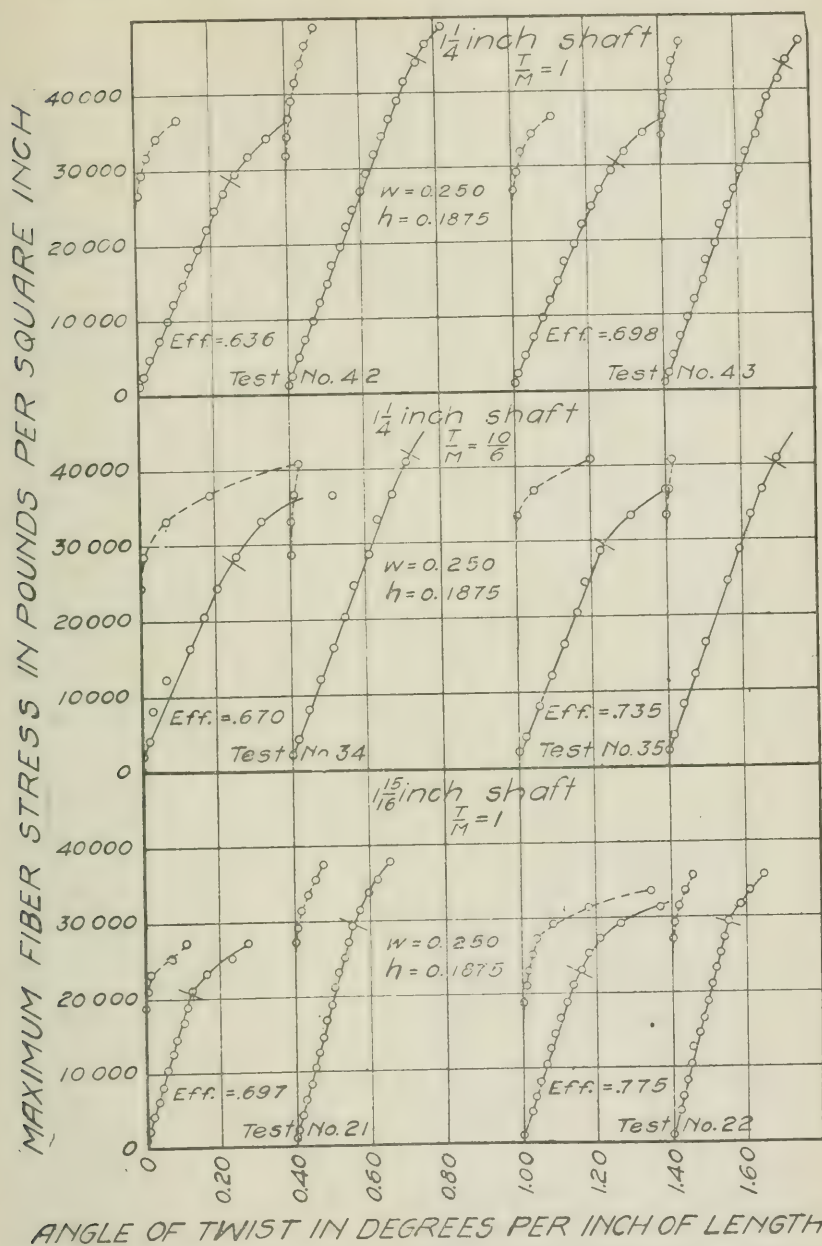


FIG. 9 DIAGRAMS OF TESTS UNDER COMBINED BENDING AND TWISTING.

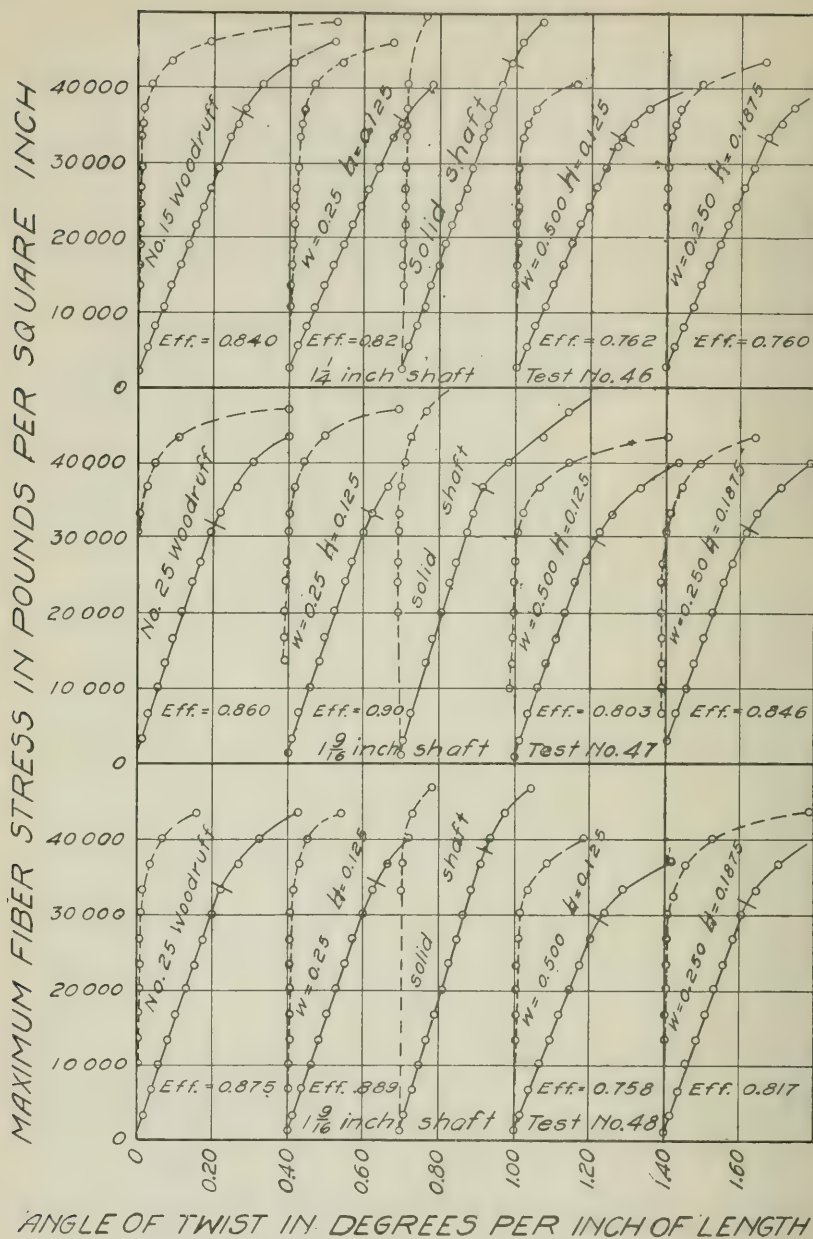


FIG. 10 DIAGRAMS OF TESTS UNDER TWISTING ONLY.

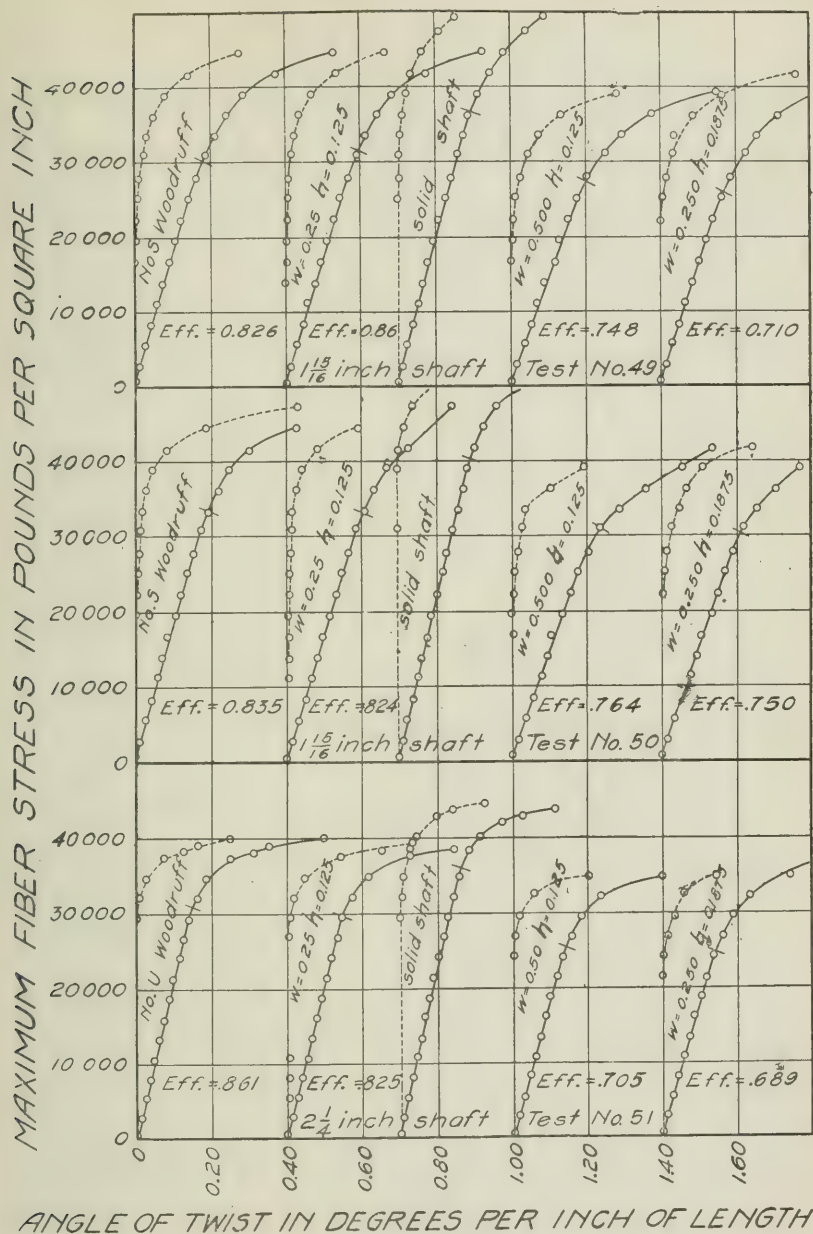


FIG. 11 DIAGRAMS OF TESTS UNDER TWISTING ONLY.

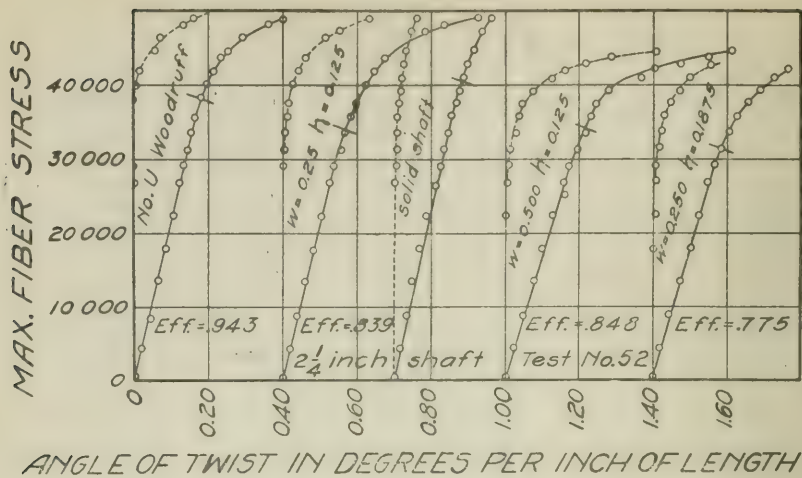


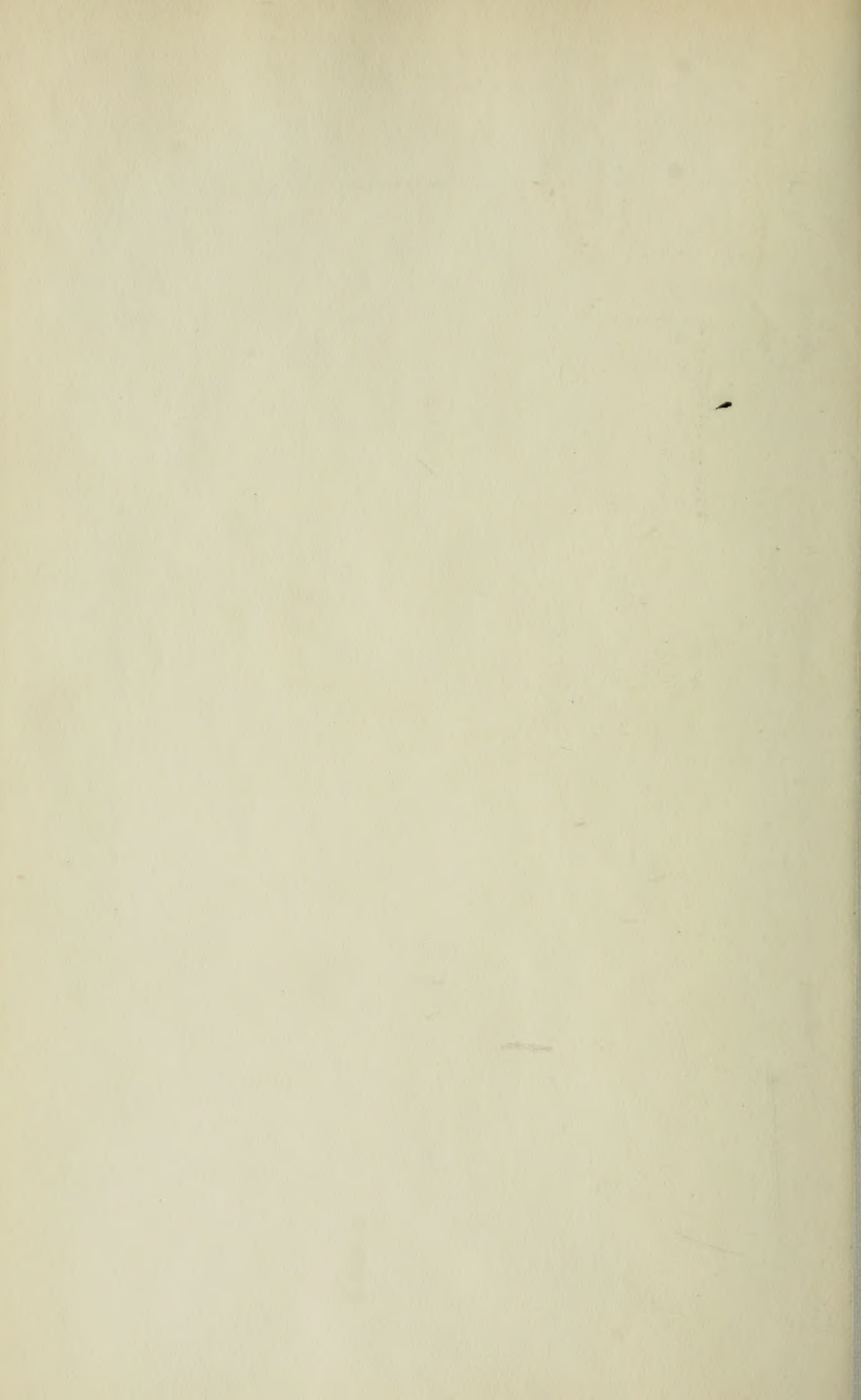
FIG. 12 DIAGRAMS OF TESTS UNDER TWISTING ONLY.

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